A NEW POWER FLOW AND SENSITIVITY ANALYSIS METHOD USING A GENERALIZED POWER FLOW ALGORITHM, INTERACTIVE COMPUTER GRAPHICS, AND ARTIFICIAL INTELLIGENCE

By

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Abstract of the Dissertation Presented to the Graduate School
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A NEW POWER FLOW AND SENSITIVITY ANALYSIS METHOD USING A GENERALIZED POWER FLOW ALGORITHM, INTERACTIVE COMPUTER GRAPHICS, AND ARTIFICIAL INTELLIGENCE

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To solve the problems of the conventional power flow methods arising from the conflicting requirements of solution speed, convergence characteristics, and the accuracy in the subsequent sensitivity analysis, a Generalized Power Flow Algorithm (GPF) has been developed in this research. As a result of the GPF derivation, a spectrum of methods become available for both power flow and sensitivity analysis.

Sensitivity analysis is used to analyze contingencies. Some contingencies create structural changes in the system necessitating modifications to the sensitivity matrix and recomputation of its inverse. A major contribution of this work involved developing and testing a transformation matrix to determine the inverse of the modified sensitivity matrix directly from the original inverse without repeating the matrix inversion process. Several case studies were conducted using the IEEE test systems. The results clearly indicate that good estimates of changes in the system state due to contingencies can be obtained using the modified sensitivity matrix. An integral part of this work consisted of using interactive computer graphics to facilitate the analyses and the numerical tests. Finally, a brief examination of how to apply a knowledge based system for solving the problem of wer system control using the GPF and sensitivity analysis was conducted and is described in the last chapter.

CHAPTER 1
INTRODUCTION

1.1 Objective of Generalized Power Flow Algorithm

Power flow calculations are performed either for on-line system operation and control or for off-line facility and operational planning. Many methods have been proposed over the years [1-8] and also are well documented in the survey by Stott [9]. Nevertheless, the choice of a solution method for practical applications is often very difficult because of the relative performance of the different methods which depends on system size, operating configurations, and available computing resources.

Currently the most widely used power flow methods in the utility industries are the Newton-Raphson (NR) method [1] and the Fast Decoupled (FD) method [3] because of their powerful convergence characteristics. Since these methods require the inverse of the Jacobian matrices, careful arrangement and ordering of the Jacobian elements based on the physical configuration of the system being solved are necessary to maximize the computational efficiency.

The NR method, which requires the inverse of a full Jacobian, has more stable convergence characteristics, but also more computationally intensive. The FD method, which is formulated by ignoring the off-diagonal submatrices in the Jacobian based on the decoupling feature of the power system, has been proposed by Stott and Alsac [3] to reduce the computational burden involved in inverting the full Jacobian.

After the power flow analysis for a base case, contingency tests are performed for secure operation of the system. Sensitivity analysis is used to analyze contingencies, and the inverse of the Jacobian matrices obtained at the power flow solution point can be utilized in the subsequent sensitivity analysis. This Jacobian based sensitivity analysis method has many advantages over the other sensitivity analysis methods, which will be explained in Chapter 4.

If a power system is normally loaded and has proper voltage magnitudes and relatively small voltage angles, the FD method may be the most efficient tool for estimating the state of the system because of its fast convergence characteristics and relatively small deviation of the sensitivity solution from their accurate values. But, for a heavily loaded system or a system which experiences large disturbances, the coupling between real power and voltage magnitude, as well as reactive power and voltage phase angle, becomes significant and neglecting the off-diagonal terms in the Jacobian, as is done in the FD method, often creates convergence problems or produces poor accuracy in the sensitivity solution. Therefore, in view of the convergence characteristics and the accuracy of the sensitivity solution, the NR method becomes preferable to the FD method. On the other hand, as the system becomes unstable, more contingency analyses are required to secure the safe operation of the system from the expected set of disturbances. Consequently, the computational time available both for the power flow and contingency analyses becomes even shorter than before. Thus, in view of the time requirement, the FD method is preferable, but the system operator may be forced to select the NR method since the FD method simply does not converge or to obtain the required accuracy in the sensitivity solution by reducing the time left for the proper contingency analyses.

To solve the problems arising from the conflicting requirements of solution speed, convergence characteristics and the solution accuracy in the subsequent sensitivity analysis, a Generalized Power Flow Algorithm (GPF) has been developed in this research. The GPF derivation yields a spectrum of power flow algorithms with varying degrees of increased computational time and solution accuracy, which enables system operators to have much more freedom in the choice of a power flow method. For a given power system operating configuration, a power flow method which exhibits the best performance can be selected.

Each power flow method in the GPF is derived with the successive simplification of the preceding method. Thus the system operator can easily change the power flow method from one method to another to obtain the optimal convergence characteristics.

One of the algorithms of GPF is the e-coupling (EC) algorithm proposed by Medanic and Abramovic [4], which retains to first order the state coupling information found in the off-diagonal submatrices of the Jacobian, but derived in a different way.

All the algorithms in GPF have been developed and tested with an 11 bus system and a 39 bus system respectively. The test results along with their algorithm implementation and convergence characteristics are explained in Chapter 3.

1.2 Need for New Sensitivity Methods

At the power flow solution point, the inverse of the Jacobian matrix obtained in the power flow computation includes sensitivity information about the system state with respect to changes in the bus injected powers. This sensitivity information can be utilized in the contingency analysis for quickly analyzing the state change in a power system created by loss of generation or redispatching, loss-of-load or load management, and line outages [10].

Contingency analysis is used by system facility planners and operation planners. System facilities planners utilize contingency analysis to determine where new capacity is needed to insure acceptable system performance in the face of possible contingencies. System operations planners utilize contingency analysis to assess the ability of the system to remain secure if contingencies occur or major system elements must be removed for maintenance. Taken collectively, there is and has been a need in the utility industry for tools that can handle a great number of analyses in relatively short periods of time. In many instances, accuracy of the solution can be sacrificed for computational efficiency as long as the information does not mislead the planner by masking the true nature of the effects of the contingencies. Moreover, it is often the case that the full solution can not be obtained since the solution does not converge for the severe contingencies especially when the system is very heavily loaded or very lightly loaded [11].

Many researchers have proposed a method that utilizes the Jacobian matrix associated with the NR or DC power flow algorithm [12-16]. Outage states are simulated assuming the scheduled demands of the end buses of the outaged elements are met. Although this method works well, it requires knowing the full Jacobian and its inverse, plus developing and inverting another matrix which relates the power injections to selected line flows. Moreover, for line outages, wide variation on the estimated states may appear for different systems and different loading conditions. The major reason for this stems from using the original base case sensitivity matrix in spite of changes in the system´s structure. Even though the modified real and reactive power injections on the end buses of the faulted line may simulate the effect of shifting the prefault power-flow on the faulted line to the other connected lines at that operating point, the original base case sensitivity matrix cannot be used to represent the system with a different structure. In fact, the sensitivity matrix for the changed system is quite different than the original base case matrix.

In Chapter 4, a new sensitivity method utilizing the sensitivity matrices obtained from the power flow solutions using the GPF has been derived. The method also describes how the new modified sensitivity matrix, which reflects the system structural change caused by the line outages, can be obtained from the original inverse without repeating the time consuming matrix inversion process. The procedure is presented along with several possible contingency cases.

1.3 Objective of the Application of Interactive Computer Graphics to Power System Analysis

The need for power system analysis has been greatly increased as power systems grow in complexity, thus necessitating the evaluation and analysis of a wide range of operating conditions or proposed expansion plans. Instead of time consuming manual tasks of preparing, processing and analyzing computer results in tabular forms full of numbers, Interactive Computer Graphics (ICG) can be utilized to significantly reduce the overall processing time.

The major reasons for application of ICG to power systems through this research are as follows:

a. Provides easy and clear vision of the system structure and operating configuration.

b. Provides prompt handling of large amounts of input and output data.

c. Facilitates rapidly obtaining results to the requested analysis.

d. Eliminates the turn around time associated with batch processing.

e. Displays the result directly on the network diagram.

f. Stores the results for future analysis or reference and easy retrieval on the CRT display.

g. Enhances the rapid interpretation of the results using color graphics.

h. Enables the operating or planning personnel to have more insight and greater creativity.

The problem of how to effectively apply the ICG techniques to power systems is described in Chapter 5. The ICG program has been developed on the Harris 800 with DEC GIGI graphics keyboard and BARCO color monitor. The program can draw any power system up to 50 buses. The system data, as well as the analysis results, can be displayed directly on the power system one line diagram. Any contingencies can be selected and applied interactively by utilizing the blinking and color changing features of the display.

1.4 Application of Artificial Intelligence to Power System Control

Once a power system state (steady or post-contingency state) is known, using one of the power flow methods and/or the sensitivity methods previously described, the system operator or planner is often confronted with the problem of how to control the system state. It is often the case that the decision should be made based on both the analytic computation and the nonanalytic computation. Nonanalytic computation may include inference, reasoning, heuristic, practice, policy, tradition and expertise, etc.

In the control of power system operating states, decisions should be made continuously on the selection of adequate control measures, control quantities, and the proper sequence of their applications. According to the recent IEEE Survey Report conducted by the IEEE Current Operational Problems Working Group using questionnaires answered by utility operating personnel across the country [17], the major operating problems of today are associated with power flow and voltage control problems. More than 90 % of those who responded to the survey indicated that the proper maintenance of power and voltage profiles during contingencies is such a complex task that better analytical aides are absolutely necessary.

Some of the major reasons why this problem is so difficult are the following:

a. There exist too few effective control variables and too many conflicting objectives. For example, generators, the main source of control in a power system, are usually connected to less than 5% of the total system buses[18]. Thus, even though some of the analytical approaches, such as Linear Programming with properly defined constraints, appear to be applicable, feasible solutions can hardly exist in most cases.

b. Power system states are difficult to determine and must be obtained by solving the power flow problem or by using appropriate sensitivity information about a given operating point. Thus, even though an experienced operator exerts a certain control measure, he is unable to know a priori the exact consequences.

c. Consequences of a given control action are difficult to determine. Control should be applied to achieve a smooth transition of the system state without violating any voltage or transmission line capacity limit.

d. Large amounts of sensitivity information should be utilized and supplemented with the operator´s "knowledge" of the system [19]. An expert operator learns through his experience the overall sensitivity of the system operation with respect to the available control actions. But as the complexity of a power system grows, it is virtually impossible for an operator to know the sensitivities of the system states for all possible operating configurations.

e. The operating configuration plus the available control quantities changes continuously. As control actions are taken, the remaining available control options should be updated. Specifically, in case of the thermal power plants, ramping rates are often limited by the permissible thermal stress or by the ramping rates of the auxiliary equipments. In addition, the amount of available capacity itself changes continuously.

In Chapter 5, a brief discussion is made on how to apply a KB system to solve these difficulties in steady state power system control problems. Harris Lisp, which is similar to MacLisp, has been used to develop a prototype program.

CHAPTER 2
STATE OF THE ART

2.1 Background

The steady state performance of a power system can be expressed with a set of nonlinear, coupled algebraic equations as follows:

$$Pi = Pgi - Pdi = \mathrm{Real}(Vi\sum_{j} YijVj)$$

$$= |Vi|\sum_{j}|Yij||Vj| \cos(\delta j - \delta i + \gamma ij) \qquad \text{--(2.1)}$$

$$Qi = Qgi - Qdi = -\mathrm{Im}(Vi\sum_{j} Yij\ Vj)$$

$$= -|Vi|\sum_{j}|Yij||Vj| \sin(\delta j - \delta i + \gamma ij) \qquad \text{--(2.2)}$$

$i,j = 1,2....n$

where

Pi, Qi	net real and reactive power injections into bus i
Pgi, Qgi	net real and reactive power generations at bus i
Pdi, Qdi	net real and reactive power demands at bus i
$\lvert Vi\rvert\angle\delta i$	complex voltage on bus i
$\lvert Yij\rvert\angle\gamma ij$	i,j th element in bus admittance matrix

From Eqs. (2.1) and (2.2), bus mismatch equations are formulated as

$$Fpi = Pgi - Pdi - \sum_{j}|Vi||Yij||Vj| \cos(\delta j - \delta i + \gamma ij) \qquad \text{--(2.3)}$$

$$Fqi = Qgi - Qdi - \sum_{j}|Vi||Yij||Vj| \sin(\delta j - \delta i + \gamma ij) \qquad \text{--(2.4)}$$

where

Fpi, Fqi : real and reactive power mismatches at bus i

Using vector notation at the solution point,

$$F(X,U,D) = \begin{bmatrix} Fp \\ Fq \end{bmatrix} \qquad \text{--- (2.5)}$$

where

F(X,U,D)	:	(2n-2) x 1 full mismatch vector
Fp	:	real power mismatch vector
Fq	:	reactive power mismatch vector
X	:	dependent state vector
U	:	independent control vector
D	:	disturbance vector
n	:	number of total buses

Several methods have been proposed to solve Eq. (2.5) for X.

2.2 Power Flow Methods

The Newton-Raphson (NR) method proposed by Tinney and Hart [1] has been the work horse in the utility industry for power flow analysis. By expanding Eq. (2.5) around the solution point using Taylor series, linearized state-update equation is obtained as follows:

$$\begin{bmatrix} H & K \\ J & L \end{bmatrix} \begin{bmatrix} \Delta X_1 \\ \Delta X_2 \end{bmatrix} = -F(X,U,D) \qquad \text{---(2.6)}$$

where

H,K,J,L : submatrices in the Jacobian

ΔX_1, ΔX_2 : state-update vectors

The above equation is then solved for state-update vector ΔX_1 and ΔX_2 with Gaussian elimination and back substitution using the optimally ordered Jacobian.

Because of the large computional burden involved in inverting the Jacobian, Stott and Alsac proposed the Fast Decoupled (FD) method[3]. In a typical power system, transmission line impedances are almost purely reactive; thus the Ybus admittance angles, γ_{ij}´s, are close to 90^o. Moreover, a power system is normally operated with line power angles, δij´s, below 30^o. As a result, the diagonal submatrix H and L dominate over the off-diagonal submatrix K and J. Thus, changes in the real power injections result in large changes in the bus voltage phase angles but give only minor effect on the bus voltage magnitudes. Similarly, changes in the reactive power injection largely affect the bus voltage magnitude while having only a minor effect on the bus voltage phase angle. Based on this decoupling feature between the power system state variables, the off-diagonal submatrices are ignored in the Jacobian resulting in the following simplified state-update equation.

$$\begin{bmatrix} H & 0 \\ 0 & L \end{bmatrix} \begin{bmatrix} \Delta X_1 \\ \Delta X_2 \end{bmatrix} = -F(X,U,D) \qquad \text{---(2.7)}$$

Thus, to solve the state-update vector, only the inverse of submatrices H and L are necessary instead of the full Jacobian.

The FD method works very well for a normally loaded power system with proper voltage levels and relatively small voltage phase angles. As the system becomes heavily loaded, or if the system includes several transmission lines with high R/X ratios, the significance of the off-diagonal submatrices increases. As a consequence, the FD method often creates a convergence problem.

Medanic and Abramovic developed the epsilon coupling (EC) power flow method to compensate for this deficiency [4]. By introducing a small parameter ε in Eq. (2.6),

$$\begin{bmatrix} H & \varepsilon K \\ \varepsilon J & L \end{bmatrix} \begin{bmatrix} \Delta X_1 \\ \Delta X_2 \end{bmatrix} = -F(X,U,D) \qquad \text{---(2.8)}$$

Expanding the above Jacobian using Taylor series about small ε and taking only the linear terms with ε value of unity, they showed that the Jacobian inverse can be approximated as

$$\begin{bmatrix} H & K \\ J & L \end{bmatrix}^{-1} \cong \begin{bmatrix} H^{-1} & -H^{-1}KL^{-1} \\ -L^{-1}JH^{-1} & L^{-1} \end{bmatrix} \qquad \text{---(2.9)}$$

Using Eq. (2.9), the changes in the state X as a function of changes in injections are

$$\begin{bmatrix} \Delta\delta \\ \\ \Delta V \end{bmatrix} = - \begin{bmatrix} H^{-1} & -H^{-1}KL^{-1} \\ \\ -L^{-1}JH^{-1} & L^{-1} \end{bmatrix} F(X,U,D) \qquad \text{---(2.10)}$$

Equation (2.10) can be used to solve for the updates, ΔX_1 and ΔX_2, to obtain the new power flow solution. In the above equation, diagonal terms are computed first and the resulting vectors are used in computing the off-diagonal coupling terms. While the Jacobian inversion is performed only for submatrices H and L like the FD method, it includes the approximated expression of the off-diagonal submatrices. For a heavily loaded system, this method is clearly superior to the FD method without significant increase in computational effort.

Instead of using a linearized update equation, Iwamoto and others [5-6] proposed a method solving the update equation retaining nonlinear terms. They utilized the quadratic expression of the power flow equations. In the Taylor series expansion of a quadratic equation, the highest order term is the 2nd order. Instead of ignoring this second order term, as is done in the NR and FD methods, they solved the mismatch equation retaining this term. While dealing with update equation, the method involves a computation with an $n^2 \times n^2$ matrix for the second order term.

Other methods can be found elsewhere [7-8].

2.3 Sensitivity Analysis

Among the various sensitivity analysis methods, methods which utilize the Jacobian matrix have the advantage of utilizing the Jacobian and its inverse which are already computed in solving the previous power flow. Researchers have proposed approximate sensitivity analysis techniques which utilize the inverse of the full size Jacobian, and some of them even require couple of iterations [12-16]. Those methods can give more accurate results than the approximate FD method, but they require the information about the inverse of the full Jacobian. With the growing popularity of the FD method in the utility industry, normally the inverse of the full Jacobian is not readily available without additional computation. Furthermore, the approximate FD technique [14] yields such a poor accuracy solution especially for a heavily loaded system that the results are often not acceptable for practical use. If the system includes several transmission lines with large R/X ratios, the results become even worse. This is mainly because of the large nodal admittance angle and subsequent growing of the significance of the off-diagonal submatrices in the Jacobian.

In most of the Jacobian based sensitivity methods, line outages are simulated using the equivalent changes in the injected power into the system at both end buses connected to the faulted line [14-16]. This was done to avoid computing the new Jacobian and its inverse to reflect the structural changes caused by the line outages. Even though the simulation appears to be equivalent with the post-fault state at that operating point, the original Jacobian inverse cannot truly represent the sensitivity of the system with a different structure.

Among other sensitivity analysis techniques, the circuit method based on Tellegen´s theorem and utilizing the adjoint network [20] seems like the most promising technique [21], which was followed by the researchers at McMasters University and others [22-24]. Other methods such as the Direct Differentiation, Injection Method, Impedance or Admittance Method etc., involve, more or less, some additional computations like composing a new sensitivity matrix or new impedance or admittance matrix [25-26].

2.4 Computer Graphics as Applied to Power Systems

The application of Interactive Computer Graphics to Power System analysis is a relatively new area. The University of Florida is among several institutions which have conducted research in this area [27]. Renssaelaer Polytechnic Institute has conducted research on computer graphics applications mainly for educational purposes (not specifically applicable to power system) [28]. Control Data Corporation has developed a training simulator and an on-line monitor using interactive graphics for operators in utilities. Utilities and consulting firms use computer graphics in engineering drafting and interactive design of power systems [29-31].

At the present stage, the development of graphics packages is being performed only by a few individual consulting firms and utilities. Stagg Systems Inc. developed a program called the Interactive Load Flow System for rapid representation of the load flow results (ex.: over voltage or under voltage is flagged with a red ´H´ or yellow ´L´, etc.). Power Technology Inc. also developed a package called the Interactive Simulator for engineering and planning, which is aimed mainly at load flow analysis, short circuit analysis and equivalent circuit formulation [32-33].

2.5 Artificial Intelligence as Applied to Power Systems

Few attempts have been made to apply Artificial Intelligence (AI) to power system areas. Sakakuchi and Matsumoto developed a knowledge based system for automatic control of a power system in the restorative state [34]. They pointed out that it is not appropriate for rapid and safe system restoration to depend mostly on the system operator´s experiences or heuristics. They also made an effort to represent those heuristics by a set of knowledge, the goal of which is to restore the power supply without overloading any transmission line. While the overload check using the load flow calculation is a numerical computation, reasoning in the Knowledge Base (KB) system is a symbolic computation. They tried to link these two different types of computations. In their study, knowledge of the system is stored in the knowledge base by a triple such as

(BUS-A, Voltage, 275.4kV), etc.

Then conditions are traced through the context tree to pick up a rule whose premise part is satisfied. The action part of the selected rule is executed and KB is modified to reflect the appropriate changes in the state. With this new change in the KB, another rule may become applicable during the next rule scanning cycle or the goal state can be achieved. For a structure of a KB system including the inference engine, refer to Fig. (2.1).

Investigators at the Virginia Polytechnic Institute and State University tried to apply AI to power system planning [35]. They utilized the concept of Analytic Hierarchy Process (AHP) proposed by Satty designed to examine the mutual dependence of various factors that lead to a decision. They insisted that AHP is useful in dealing with uncertainty in electric utility planning and tried to quantify various divergencies of opinions, practices and events, etc.

Other researchers utilized pattern recognition techniques in power system analysis [36-40]. Instead of computing the power system state numerically, they set so called target states using some of the real time states. Then these target states are trained by comparing them to a large number of pre-disturbance states already studied. To predict a power system state, they select a set of representative states based on the availability of telemetering, intuition gained from experience, engineering judgement, and any correlation from the regression analysis, etc., which is called a feature of the state. The feature of a state thus selected is compared with the target states, and the approximated state can be obtained from the precalculated state of the nearest target state.

To date, progress in the area of the application of AI to power systems has been modest. However, the future looks very promising for successful application of AI techniques to power systems.

CHAPTER 3
GENERALIZED POWER FLOW ALGORITHM

The major objective of the Generalized Power Flow Algorithm (GPF) derived in this chapter is to provide the system operator or planner with much freedom in choosing a power flow method which is best suited to the accuracy and time requirements and, more importantly, converges to the solution for a given operating configuration. Starting from the Decoupled Newton-Raphson(NR) method, which is equivalent to the conventional NR method but derived using only the Jacobian submatrices, each successive algorithm is obtained from gradual simplification of the preceding algorithm. Therefore, smooth transition from one method to another is possible during the real time operation or even between the each iteration, which adds further flexibility in power flow computation.

3.1 Derivation of GPF

From Eqs. (2.3) and (2.4), power flow mismatch equations can be expressed as

$$Fpi = Pgi - Pdi - \sum_{j}|Vi||Yij||Vj| \cos(\delta j - \delta i + \gamma ij) \qquad \text{--(3.1)}$$

$$Fqi = Qgi - Qdi + \sum_{j}|Vi||Yij||Vj| \sin(\delta j - \delta i + \gamma ij) \qquad \text{--(3.2)}$$

$$i,j=1,2 \ldots\ldots n$$

Then power flow mismatch at the solution point due to the state change can be written as

$$\begin{bmatrix} Fp \\ \\ Fq \end{bmatrix} = \begin{bmatrix} \Delta P \\ \\ \Delta Q \end{bmatrix} = \begin{bmatrix} \dfrac{\partial Fp}{\partial X_1} & \dfrac{\partial Fp}{\partial X_2} \\ \dfrac{\partial Fq}{\partial X_1} & \dfrac{\partial Fq}{\partial X_2} \end{bmatrix} \begin{bmatrix} \Delta X_1 \\ \\ \Delta X_2 \end{bmatrix} = \begin{bmatrix} H & K \\ \\ J & L \end{bmatrix} \begin{bmatrix} \Delta X_1 \\ \\ \Delta X_2 \end{bmatrix} \qquad \text{--(3.3)}$$

where

$$X_1 = \begin{bmatrix} \delta 2 \\ \delta 3 \\ \cdot \\ \cdot \\ \cdot \\ \delta n \end{bmatrix} \qquad X_2 = \begin{bmatrix} Qg_1 \\ Qg_2 \\ \cdot \\ \cdot \\ Qgg \\ Vg_{+1} \\ \cdot \\ \cdot \\ Vgn \end{bmatrix} \qquad \text{--(3.4)}$$

n : total no. of buses
g : total no. of generators

From Eq. (3.3)

$$\Delta P = H\,\Delta X_1 + K\,\Delta X_2 \qquad \text{--- (3.5)}$$

$$\Delta Q = J\,\Delta X_1 + L\,\Delta X_2 \qquad \text{--- (3.6)}$$

From Eqs. (3.1) and (3.2), since submatrix K has several columns with all zeros as their elements, K becomes a singular matrix and does not have an inverse. However, Fqi includes δi term and its diagonal elements always become nonzero, i.e., submatrix J is nonsingular and has an inverse.

Multiplying both sides of Eq. (3.5) by H^{-1} and (3.6) by J^{-1} respectively

$$H^{-1}\Delta P = \Delta X_1 + H^{-1}K\,\Delta X_2 \qquad \text{---}\ (3.7)$$

$$J^{-1}\Delta Q = \Delta X_1 + J^{-1}L\,\Delta X_2 \qquad \text{---}\ (3.8)$$

Subtracting Eq. (3.8) from (3.7) yields

$$H^{-1}\Delta P - J^{-1}\Delta Q = (\,H^{-1}K - J^{-1}L\,)\,\Delta X_2 \qquad \text{---}\ (3.9)$$

From Eq. (3.9), even though $H^{-1}K$ becomes singular because of K, ($H^{-1}K - J^{-1}L$) can hardly be singular since $J^{-1}L$ is nonsingular. Solving for ΔX_2

$$\begin{aligned}\Delta X_2 &= (\,H^{-1}K - J^{-1}L\,)^{-1}(\,H^{-1}\Delta P - J^{-1}\Delta Q)\\ &= [\,-J^{-1}L\,\{\,I - (\,J^{-1}L\,)^{-1}H^{-1}K\,\}]^{-1}(H^{-1}\Delta P - J^{-1}\Delta Q)\\ &= -\{\,I - (\,L^{-1}J\,H^{-1})K\,\}^{-1}L^{-1}J(\,H^{-1}\Delta P - J^{-1}\Delta Q)\\ &= -\{\,I - (\,L^{-1}J\,H^{-1})K\,\}^{-1}(\,L^{-1}JH^{-1}\Delta P - L^{-1}\Delta Q)\end{aligned}$$

$$\text{---}(3.10)$$

By substituting ΔX_2 computed from Eq. (3.10) into Eq. (3.5),

$$\Delta X_1 = H^{-1}(\,\Delta P - K\,\Delta X_2) \qquad \text{---}(3.11)$$

Starting from Eqs. (3.10) and (3.11), gradual simplification of the two equations is possible, which yields a set of power flow methods among which the conventional EC and FD methods also happen to be included. For convenience, title is assigned to each method.

i. Decoupled NR method

Rewriting the previous results,

$$\Delta X_2 = - \{ I - (L^{-1} J H^{-1}) K \}^{-1} (L^{-1} J H^{-1} - \Delta P - L^{-1} \Delta Q) \qquad \text{---}(3.12)$$

$$\Delta X_1 = H^{-1} (\Delta P - K \Delta X_2) \qquad \text{---}(3.13)$$

Since Eqs. (3.10) and (3.11) have been derived without any simplification, they are expected to be compatible with the full NR method in their solution accuracy.

ii. Accelerated NR method

The submatrices K and H and the real power mismatch ΔP in Eq. (3.13) can be updated using the update state vector ΔX_2 computed from Eq. (3.12), which yields

$$\Delta X_1 = \tilde{H}^{-1} (\Delta\tilde{P} - \tilde{K} \Delta X_2) \qquad \text{---}(3.14)$$

where

$\tilde{H}^{-1}$: inverse of updated H
$\tilde{K}$: updated K
$\Delta\tilde{P}$: updated real power mismatch

iii. Improved Version 1 of the EC method

Under the assumption that the spectral radius of $L^{-1} J H^{-1} K$ is less than unity and utilizing the Neuman series expansion, 1st term in RHS in Eq. (3.12) can be expanded as [41-42]

$$\{ I - (L^{-1} J H^{-1}) K \}^{-1} = I + (L^{-1} J H^{-1}) K + \{ (L^{-1} J H^{-1}) K \}^2 + \ldots$$

By taking up to the first order term,

$$\{ I - (L^{-1}JH^{-1})K \}^{-1} \cong I + (L^{-1}JH^{-1})K$$

The accuracy of the above approximation increases as the norm of the matrix $(L^{-1}JH^{-1})K$ becomes small. This is the advantage of computing ΔX_2 first since the elements of $(H^{-1}KL^{-1})J$ are much larger than those of the $(L^{-1}JH^{-1})K$ in actual power systems

Therefore Eq. (3.10) can be approximated as

$$\Delta X_2 \cong - \{ I + (L^{-1}JH^{-1})K \}(L^{-1}JH^{-1}\Delta P - L^{-1}\Delta Q) \qquad \text{--- (3.16)}$$

Notice that the 2nd term of the RHS in Eq. (3.16) is identical with the expression appeared in the conventional EC method. This fact implies that the first term, $\{ I + (L^{-1}JH^{-1})K \}$, can be interpreted as an accuracy improving factor over the EC method.

iv. Improved version 2 of the EC method

From Eq. (3.16), by ignoring $\{ I + (L^{-1}JH^{-1})K \}$,

$$\Delta X_2 = - L^{-1}JH^{-1}\Delta P + L^{-1}\Delta Q \qquad \text{--- (3.17)}$$

Substitution of the above expression into Eq. (3.13) yields

$$\begin{aligned}\Delta X_1 &= H^{-1} (\Delta P - K\Delta X_2) \\ &= H^{-1}\{ \Delta P - K(-L^{-1}JH^{-1}\Delta P + L^{-1}\Delta Q) \} \\ &= H^{-1}\{ \Delta P + K(L^{-1}JH^{-1}) \Delta P - KL^{-1}\Delta Q \}\end{aligned}$$

$$= H^{-1}\{ I + (L^{-1}JH^{-1})K \} \Delta P - H^{-1}KL^{-1}\Delta Q \quad \text{--- (3.18)}$$

If the term $\{ I + (L^{-1}JH^{-1})K \}$ is ignored again, Eq. (3.18) coincides with the conventional EC method. In actual algorithm implementation, naturally ΔX_1 is computed using Eq. (3.13) instead of Eq. (3.18). Equation (3.18) is simply derived to show the embedded accuracy enhancement in computing ΔX_1 by using the updated ΔX_2. Indeed, the numerical test results, which will be explained in the next section, show significant improvement in the solution accuracy.

v. EC method

Again ignoring $\{ I + (L^{-1}JH^{-1})K \}$ in Eq. (3.18),

$$\Delta X_1 = H^{-1}\Delta P - H^{-1}KL^{-1}\Delta Q \quad \text{--- (3.19)}$$

Together with Eq. (3.17), they are identical with the conventional EC method.

vi. Improved FD method

From Eq. (3.17), dropping the 1st order approximation term on the RHS,

$$\Delta X_2 = L^{-1}\Delta Q \quad \text{--- (3.20)}$$

By substituting into Eq. (3.13),

$$\Delta X_1 = H^{-1} (\Delta P - KL^{-1}\Delta Q) \quad \text{--- (3.21)}$$

Again, $-KL^{-1}\Delta Q$ in the above equation can be considered as an accuracy improving factor over the conventional FD method.

vii. FD method

By ignoring $KL^{-1}\Delta Q$ in Eq. (3.21), finally we can get

$$\Delta X_1 = H^{-1}\Delta P \qquad \text{--- (3.22)}$$

Together with Eq. (3.20), Eq. (3.22) becomes the FD method.

3.2 Computational Algorithm and Numerical Test Results

3.2.1 Program development

A computer program has been developed using FORTRAN 77 to test all the power flow methods in the GPF, which were derived in the previous section. Harris H-800 computer with 1.5 M Bytes of main CPU memory, installed in Larson Hall, has been used.

The developed power system analysis program can be run with a macro file named "POWER.MAC". Properly prepared data files for any power system up to 50 buses in size can be copied into input data file "DATAIN". Data files for the 3 bus, 7 bus, 11 bus and 39 bus systems are prepared in the files named "DATA3", "DATA7", "DATA11" and "DATA39" respectively. Analyses can be performed interactively and all the results, which can be displayed on the screen, are copied into output data file called "RESULT". The block flow chart of the developed program is shown in Fig. (3.1).

The largest computational burden in power flow calculation involves inverting the Jacobian matrix. It is common to use Gaussian Elimination and back substitution in conjunction with schemes for optimally ordering the rows and columns to minimize the fill-ins, and hence, the storage requirement and the computation time [43-45]. During the upper triangularization period, it is necessary to store the multiplying factors to restore the explicit inverse of the Jacobian for the subsequent sensitivity analysis. The multiplying factors can be stored in the same memory space by replacing the eliminated elements in the lower triangular part. Since the program has been developed for general power systems, the optimal ordering of the Jacobian and the sparse matrix technique, which largely depend on the physical configuration of the specific power system of interest, have not been implemented in the program. Thus the CPU time should be used only for the relative comparison of the convergency speed between each power flow method.

3.2.2 Convergency characteristics

As a convergence criterion, $\varepsilon = 10^{-4}$ was used for the absolute values of ΔV and $\Delta\delta$ or for the real and reactive power mismatches, ΔP and ΔQ, whichever converge first. The convergency criteria can be changed interactively. Convergency criteria were applied both for voltages and

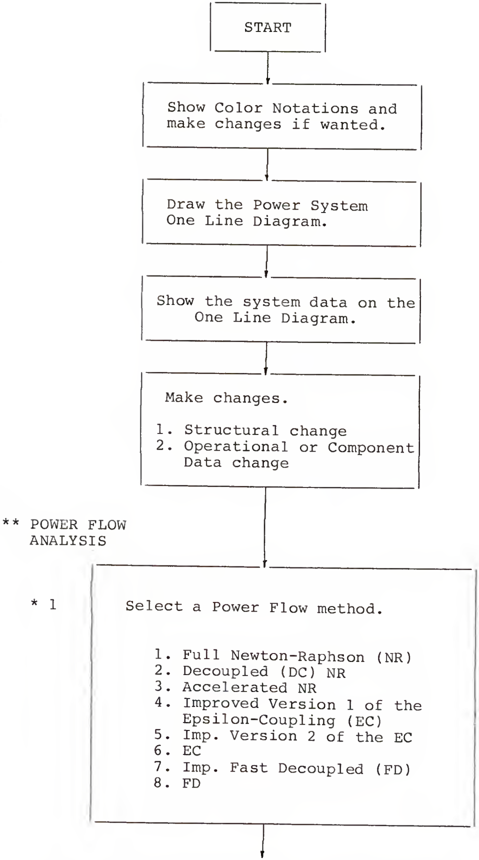
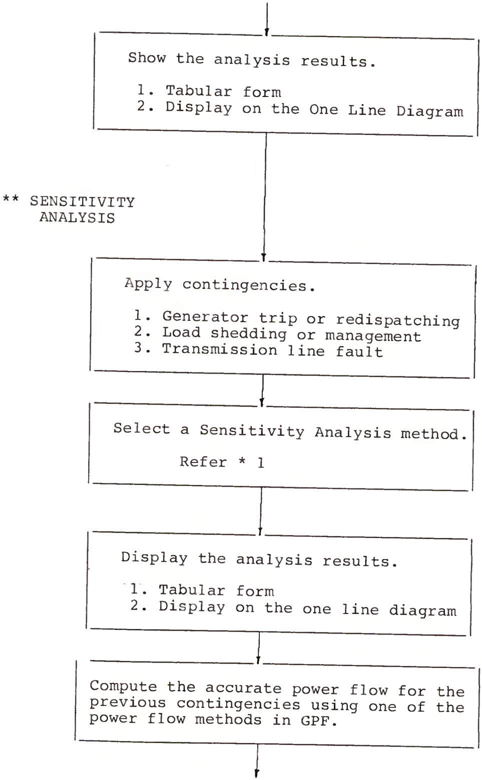

START
Show Color Notations and make changes if wanted.
Draw the Power System One Line Diagram.
Show the system data on the One Line Diagram.
Make changes.
1. Structural change
2. Operational or Component Data change
** POWER FLOW ANALYSIS
* 1
Select a Power Flow method.
1. Full Newton-Raphson (NR)
2. Decoupled (DC) NR
3. Accelerated NR
4. Improved Version 1 of the Epsilon-Coupling (EC)
5. Imp. Version 2 of the EC
6. EC
7. Imp. Fast Decoupled (FD)
8. FD

Fig. 3.1 Block Flow Chart of the Interactive Power System Analysis Program



Show the analysis results.

1. Tabular form
2. Display on the One Line Diagram

** SENSITIVITY ANALYSIS

Apply contingencies.

1. Generator trip or redispatching
2. Load shedding or management
3. Transmission line fault

Select a Sensitivity Analysis method.

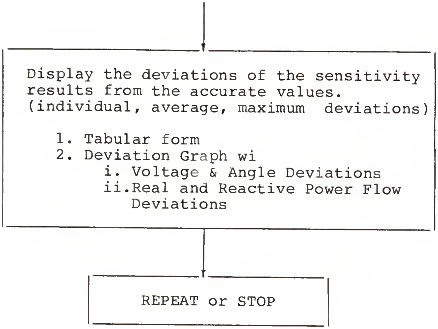
Refer * 1

Display the analysis results.

1. Tabular form
2. Display on the one line diagram

Compute the accurate power flow for the previous contingencies using one of the power flow methods in GPF.

Fig. 3.1-continued



Display the deviations of the sensitivity results from the accurate values. (individual, average, maximum deviations)

1. Tabular form
2. Deviation Graph wi
    - i. Voltage & Angle Deviations
    - ii. Real and Reactive Power Flow Deviations

REPEAT or STOP

Fig. 3.1-continued

power mismatches since the power mismatch sometimes can not converge while the voltage does especially in the approximated power flow methods.

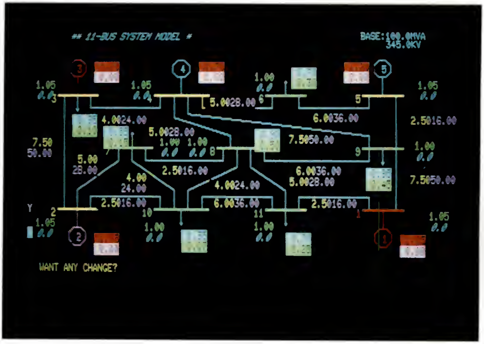
Since ΔX_2 appears in the expression of ΔX_1, better convergency results by not updating power mismatches after computing ΔX_2 in each iteration. The same thing is also applicable to updating the Jacobian with the results of the computation of ΔX_2. Thus, it turned out that the convergency characteristic of the Accelerated NR method is not superior to that of the Decoupled NR method. The computational burden of computing the first term on the RHS in ΔX_2 expression in the Decoupled NR method needs to be compared with that of the full NR method for each spscific power system of interest. The advantage of the Decoupled NR method over the full NR method is that it deals with the Jacobians of half sizes. Since the submatrix K and J are computed separately, it is relatively easy to formulate the block diagonal matrices in ordering the Jacobians, which facilitates the implementation of the minimum fill-in schemes in the inverse process. Another advantage is that it is possible to test the convergency of the update vectors, ΔX_1 and ΔX_2, separately. Once one of the update vectors is converged, it is necessary to iterate only the remaining vector. But the difficulties in applying the back substitution are the disadvantage of the Decoupled NR method compared with the full NR method. For computing ΔX_2 in other algorithms, $L^{-1}\Delta Q$ and $H^{-1}\Delta P$ are computed first, and the resulting vectors are multiplied with subsequent matrices to reduce the overall computation time.

Power flows for the 11 bus and 39 bus systems as shown in Figs. (3.2) and (3.3) have been calculated using all the power flow methods in GPF algorithm. All of the methods were well converged to the solution in most cases and the results are shown in Tables (3.1)-(3.18) attached at the end of this chapter together with their system data.

The convergency characteristics for each power flow method, which shows the largest mismatches in ΔP and ΔQ in each iteration, are shown along with its CPU time in Figs. (3.4) and (3.5). In some cases, the iteration stopped even though the power mismatches are larger than the convergency criteria. This implies that the state update vectors, ΔV and $\Delta\delta$, had satisfied the convergency criteria instead of the power mismatches.

As expected, simplification of Eq. (3.12) into Eq. (3.16) resulted in significant computational time savings. From the Improved Version 1 of the EC method up to the FD method, their computational times are of different orders compared to those of the NR compatible methods. Especially, the computational time and the convergence characteristic of the Improved Version 1 of the EC method is impressive.

Without any specific optimization of the computational algorithm, overall computational time of the Decoupled NR method is about 65 % of that of the full NR method for the 39 Bus system. The computation time of the Improved version

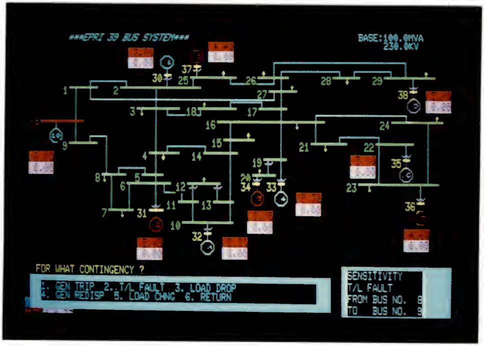


## 11-BUS SYSTEM MODEL \#

BASE:100.0MVA
345.0KV

WANT ANY CHANGE?

Fig. 3.2 Display of the 11 Bus System One Line Diagram

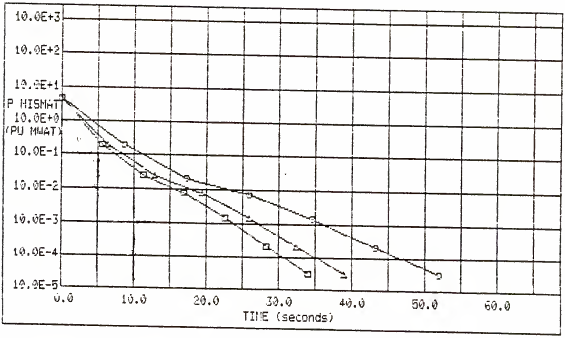


```
***EPRI 39 BUS SYSTEM***                              BASE:100.0MVA
                                                           230.0KV
```

```
FOR WHAT CONTINGENCY ?
1. GEN TRIP  2..T/L FAULT  3. LOAD DROP
4. GEN REDISP  5. LOAD CHNG  6. RETURN
```

```
SENSITIVITY
T/L FAULT
FROM BUS NO.  8
TO   BUS NO.  9
```

Fig. 3.3 Display of the 39 Bus System One Line Diagram



* Full NR : ○———○
DC NR : △———△
Acc. NR : □———□

Fig. 3.4 Real Power Convergence Characteristics for the 39 Bus System

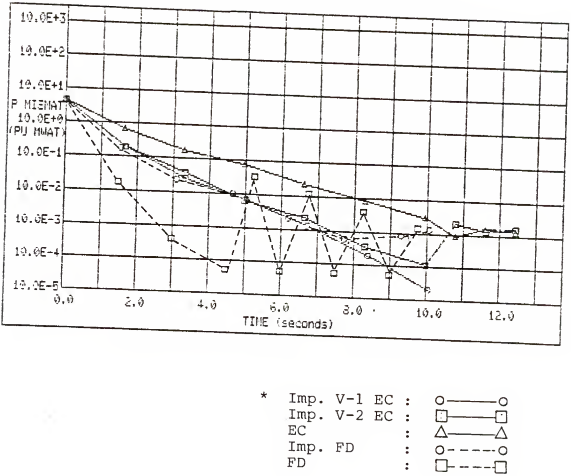
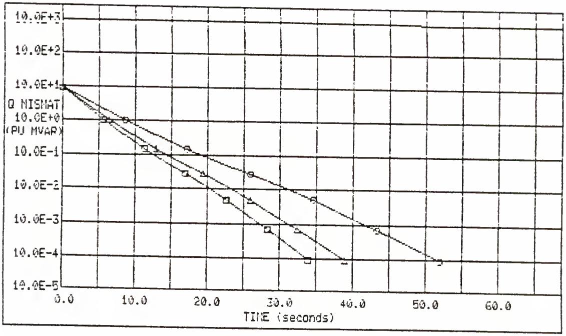
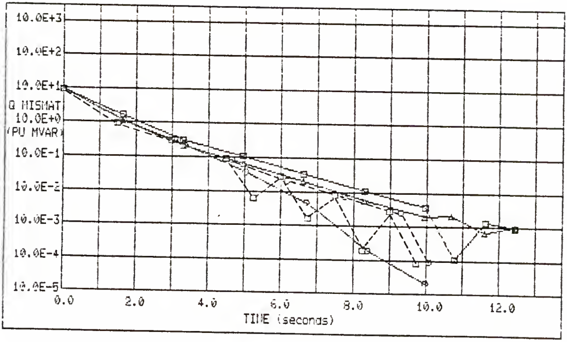


Fig. 3.4-continued



* Full NR : ○———○
DC NR : △———△
Acc. NR : □———□

Fig. 3.5 Reactive Power Convergence Characteristics for the 39 Bus System



* Imp. V-1 EC : ○——○
Imp. V-2 EC : □——□
EC : △——△
Imp. FD : ○------○
FD : □------□

Fig. 3.5-continued

2 of the EC method is almost same with that of the EC method. This is mainly because of the reduced time in computing ΔX_1 even though more calculations are involved in computing ΔX_2.

The effects of the transmission line R/X ratios on the convergency characteristics together with the maximum eigenvalues of $(L^{-1}JH^{-1})K$ are shown in Table (3.19). As is mentioned previously, power flow solutions are hard to converge as the R/X ratios grow. The FD method is affected most as expected. By increasing the value of average R/X ratio from 0.23 up to 0.50 in the 11 Bus system, a couple of methods do not converge to the solution. Moreover the maximum eigenvalues of $(L^{-1}JH^{-1})K$ is very sensitive to the changes in R/X ratios. It clearly shows that the power flow becomes hard to converge as the maximum eigenvalue approaches unity. In the test systems, the maximum eigenvalues of $(L^{-1}JH^{-1})K$ were -0.025 for the 11 Bus system and -0.38 for the 39 Bus system at the solution points. It is also remarkable that the Improved FD method exhibits a strong and stable convergence characteristic which is almost compatible with that of the full NR method.

The ratio of the computational time of each method to the full NR method becomes smaller as the system size grows. Accordingly, significant decrease of these computational time ratios are expected for large systems.

Among several interesting features, the convergency characteristic of the Improved Version 1 of the EC method and the Improved FD method are superior to those of the conventional EC and the FD method respectively. Because of their powerful convergency characteristics, number of iterations required for convergence are often less than those of the EC or the FD method. In case of the Improved FD method, since the computational time increase for one iteration over the FD method is trivial as shown in the previous section, overall computational time is sometimes even shorter than that of the FD method. Thus, the Improved FD method shows a very good potential of wide application to the utilities in the future.

Table 3.1 System Data for the 11 Bus System

* Base : 100.0 MVA 345.0 KV
* No. of Lines : 17
* No. of Generators : 5
* No. of Loads : 7

* T/L Data

NO.	FBS	TBS	R(%)	X(%)	MVAC	|YS|	GAM	|YP|
1	1	9	7.50	50.00	0.0	2.0	0.0	0.0
2	1	11	2.50	16.00	0.0	6.2	0.0	0.0
3	2	3	7.50	50.00	0.0	2.0	0.0	0.0
4	2	7	5.00	28.00	0.0	3.5	0.0	0.0
5	2	10	2.50	16.00	0.0	6.2	0.0	0.0
6	3	4	4.00	24.00	0.0	4.1	0.0	0.0
7	4	6	5.00	28.00	0.0	3.5	0.0	0.0
8	4	8	5.00	28.00	0.0	3.5	0.0	0.0
9	4	9	7.50	50.00	0.0	2.0	0.0	0.0
10	5	6	6.00	36.00	0.0	2.7	0.0	0.0
11	5	9	2.50	16.00	0.0	6.2	0.0	0.0
12	7	8	2.50	16.00	0.0	6.2	0.0	0.0
13	7	10	4.00	24.00	0.0	4.1	0.0	0.0
14	8	9	6.00	36.00	0.0	2.7	0.0	0.0
15	8	10	4.00	24.00	0.0	4.1	0.0	0.0
16	8	11	5.00	28.00	0.0	3.5	0.0	0.0
17	10	11	6.00	36.00	0.0	2.7	0.0	0.0

* Generation Data

GEN NO	BUS NO	BUS TYP	RATED CAP MVA	AVAILAB CAP MVA	CURRENT GENERAT.	
					MW	MVAR
1	1	S	300.0	300.0	105.0	
2	2	V	500.0	500.0	105.0	
3	3	V	250.0	250.0	90.0	
4	4	V	200.0	200.0	70.0	
5	5	V	200.0	200.0	120.0	

* Load Data

LOAD NO.	BUS NO.	*LOAD CAPACITY*	
		MW	MVAR
1	3	35.0	10.0
2	6	70.0	30.0
3	7	55.0	15.0
4	8	90.0	50.0
5	9	95.0	45.0
6	10	35.0	7.0
7	11	70.0	25.0

Table 3.2 Power Flow Results for the 11 Bus System
(Full NR Method)

```
* Power:  Full NR Method

* No. of Iterations :  6


*--  BUS DATA ---*   *GENERATION*  *---LOAD---*  *REAC*     *---  LINE FLOW ---*
BS TY  VOLTS ANGLE     MW   MVAR     MW    MVAR    MVAR      TO LN     MW      MVAR

 1 S 1.05000   0.00   76.3  54.3    0.0    0.0     0.0
                                                            --------------------
                                                             9  1     10.7   13.7
 2 V 1.05000   2.33  105.0  63.0    0.0    0.0     0.0      11  2     65.6   40.6
                                                            --------------------
                                                             3  3    -17.5    3.3
                                                             7  4     51.0   25.1
 3 V 1.05000   7.01   90.0   3.4   35.0   10.0     0.0      10  5     71.5   34.5
                                                            --------------------
                                                             2  3     17.7   -1.9
 4 V 1.05000   2.26   70.0  73.4    0.0    0.0     0.0       4  6     37.3   -4.6
                                                            --------------------
                                                             3  6    -36.8    7.7
                                                             6  7     34.4   22.6
                                                             8  8     53.7   30.2
 5 V 1.05000   4.44  120.0  56.1    0.0    0.0     0.0       9  9     18.7   13.0
                                                            --------------------
                                                             6 10     37.3   17.2
 6 L 0.97681  -2.50    0.0   0.0   70.0   30.0     0.0       9 11     82.7   38.9
                                                            --------------------
                                                             4  7    -33.6  -18.3
 7 L 0.96662  -5.04    0.0   0.0   55.0   15.0     0.0       5 10    -36.4  -11.7
                                                            --------------------
                                                             2  4    -49.5  -17.0
                                                             8 12      5.8    7.6
 8 L 0.95261  -5.50    0.0   0.0   90.0   50.0     0.0      10 13    -11.3   -5.6
                                                            --------------------
                                                             4  8    -51.9  -20.6
                                                             7 12     -5.8   -7.4
                                                             9 14    -14.6   -3.9
                                                            10 15    -15.1  -10.3
 9 L 0.97798  -2.42    0.0   0.0   95.0   45.0     0.0      11 16     -2.6   -7.7
                                                            --------------------
                                                             1  1    -10.5  -12.3
                                                             4  9    -18.4  -10.7
                                                             5 11    -80.8  -26.8
10 L 0.98555  -3.54    0.0   0.0   35.0    7.0     0.0       8 14     14.7    4.8
                                                            --------------------
                                                             2  5    -70.1  -25.4
                                                             7 13     11.4    6.0
                                                             8 15     15.3   11.2
11 L 0.97664  -5.30    0.0   0.0   70.0   25.0     0.0      11 17      8.4    1.2
                                                            --------------------
                                                             1  2    -64.2  -32.0
                                                             8 16      2.6    7.9
                                                            10 17     -8.4   -0.9
                    ------------ ----- ------   -------
        TOTALS      461.3  250.3  450.0  182.0     0.0
```

Table 3.3 Power Flow Results for the 11 Bus System
(Decoupled NR Method)

```
* Power Flow Method :  Decoupled NR Method
* No. of Iterations :  4.5

*--  BUS DATA ---*   *GENERATION*   *---LOAD---*   *REAC*    *---  LINE FLOW   ---*
BS TY  VOLTS ANGLE      MW   MVAR     MW    MVAR    MVAR     TO LN      MW      MVAR

                                                             --------------------
 1 S 1.05000   0.00   76.3   54.3    0.0    0.0     0.0       9  1      10.7    13.7
                                                             11  2      65.6    40.6
                                                             --------------------
 2 V 1.05000   2.33  105.0   63.0    0.0    0.0     0.0       3  3     -17.5     3.3
                                                              7  4      51.0    25.1
                                                             10  5      71.5    34.5
                                                             --------------------
 3 V 1.05000   7.01   90.0    3.4   35.0   10.0     0.0       2  3      17.7    -1.9
                                                              4  6      37.3    -4.6
                                                             --------------------
 4 V 1.05000   2.26   70.0   73.4    0.0    0.0     0.0       3  6     -36.8     7.7
                                                              6  7      34.4    22.6
                                                              8  8      53.7    30.2
                                                              9  9      18.7    13.0
                                                             --------------------
 5 V 1.05000   4.44  120.0   56.1    0.0    0.0     0.0       6 10      37.3    17.2
                                                              9 11      82.7    38.9
                                                             --------------------
 6 L 0.97681  -2.50    0.0    0.0   70.0   30.0     0.0       4  7     -33.6   -18.3
                                                              5 10     -36.4   -11.7
                                                             --------------------
 7 L 0.96662  -5.04    0.0    0.0   55.0   15.0     0.0       2  4     -49.5   -17.0
                                                              8 12       5.8     7.6
                                                             10 13     -11.3    -5.6
                                                             --------------------
 8 L 0.95261  -5.50    0.0    0.0   90.0   50.0     0.0       4  8     -51.9   -20.6
                                                              7 12      -5.8    -7.4
                                                              9 14     -14.6    -3.9
                                                             10 15     -15.1   -10.3
                                                             11 16      -2.6    -7.7
                                                             --------------------
 9 L 0.97798  -2.42    0.0    0.0   95.0   45.0     0.0       1  1     -10.5   -12.3
                                                              4  9     -18.4   -10.7
                                                              5 11     -80.8   -26.8
                                                              8 14      14.7     4.8
                                                             --------------------
10 L 0.98555  -3.54    0.0    0.0   35.0    7.0     0.0       2  5     -70.1   -25.4
                                                              7 13      11.4     6.0
                                                              8 15      15.3    11.2
                                                             11 17       8.4     1.2
                                                             --------------------
11 L 0.97664  -5.30    0.0    0.0   70.0   25.0     0.0       1  2     -64.2   -32.0
                                                              8 16       2.6     7.9
                                                             10 17      -8.4    -0.9
                    ------------- ----- ------  -------
         TOTALS     461.3  250.3  450.0  182.0      0.0
```

Table 3.4 Power Flow Results for the 11 Bus System
(Accelerated DC NR Method)

```
* Power Flow Method :   Accelerated DC NR Method
* No. of Iterations :   4.5

*--  BUS DATA ---*   *GENERATION*  *---LOAD---*  *REAC*     *---  LINE FLOW    ---*
BS TY  VOLTS ANGLE      MW   MVAR     MW   MVAR    MVAR      TO LN      MW     MVAR

 1 S 1.05000  0.00    76.3   54.3    0.0    0.0     0.0      ----------------------
                                                              9  1     10.7   13.7
 2 V 1.05000  2.33   105.0   63.0    0.0    0.0     0.0      11  2     65.6   40.6
                                                             ----------------------
                                                              3  3    -17.5    3.3
                                                              7  4     51.0   25.1
 3 V 1.05000  7.01    90.0    3.4   35.0   10.0     0.0      10  5     71.5   34.5
                                                             ----------------------
                                                              2  3     17.7   -1.9
 4 V 1.05000  2.26    70.0   73.4    0.0    0.0     0.0       4  6     37.3   -4.6
                                                             ----------------------
                                                              3  6    -36.8    7.7
                                                              6  7     34.4   22.6
                                                              8  8     53.7   30.2
 5 V 1.05000  4.44   120.0   56.1    0.0    0.0     0.0       9  9     18.7   13.0
                                                             ----------------------
                                                              6 10     37.3   17.2
 6 L 0.97681 -2.50     0.0    0.0   70.0   30.0     0.0       9 11     82.7   38.9
                                                             ----------------------
                                                              4  7    -33.6  -18.3
 7 L 0.96662 -5.04     0.0    0.0   55.0   15.0     0.0       5 10    -36.4  -11.7
                                                             ----------------------
                                                              2  4    -49.5  -17.0
                                                              8 12      5.8    7.6
 8 L 0.95261 -5.50     0.0    0.0   90.0   50.0     0.0      10 13    -11.3   -5.6
                                                             ----------------------
                                                              4  8    -51.9  -20.6
                                                              7 12     -5.8   -7.4
                                                              9 14    -14.6   -3.9
                                                             10 15    -15.1  -10.3
 9 L 0.97798 -2.42     0.0    0.0   95.0   45.0     0.0      11 16     -2.6   -7.7
                                                             ----------------------
                                                              1  1    -10.5  -12.3
                                                              4  9    -18.4  -10.7
                                                              5 11    -80.8  -26.8
10 L 0.98555 -3.54     0.0    0.0   35.0    7.0     0.0       8 14     14.7    4.8
                                                             ----------------------
                                                              2  5    -70.1  -25.4
                                                              7 13     11.4    6.0
                                                              8 15     15.3   11.2
11 L 0.97664 -5.30     0.0    0.0   70.0   25.0     0.0      11 17      8.4    1.2
                                                             ----------------------
                                                              1  2    -64.2  -32.0
                                                              8 16      2.6    7.9
                                                             10 17     -8.4   -0.9
                    ------ ------ ------ ------  -------
         TOTALS      461.3  250.3  450.0  182.0     0.0
```

Table 3.5 Power Flow Results for the 11 Bus System
(Imp. Version 1 EC Method)

* Power Flow Method : Imp. Version 1 EC Method

* No. of Iterations : 4.5

-- BUS DATA ---				*GENERATION*		*---LOAD---*		*REAC*	*--- LINE FLOW ---*			
BS	TY	VOLTS	ANGLE	MW	MVAR	MW	MVAR	MVAR	TO	LN	MW	MVAR
1	S	1.05000	0.00	76.3	54.3	0.0	0.0	0.0	9	1	10.7	13.7
									11	2	65.6	40.6
2	V	1.05000	2.33	105.0	63.0	0.0	0.0	0.0	3	3	-17.5	3.3
									7	4	51.0	25.1
									10	5	71.5	34.5
3	V	1.05000	7.01	90.0	3.4	35.0	10.0	0.0	2	3	17.7	-1.9
									4	6	37.3	-4.6
4	V	1.05000	2.26	70.0	73.4	0.0	0.0	0.0	3	6	-36.8	7.7
									6	7	34.4	22.6
									8	8	53.7	30.2
									9	9	18.7	13.0
5	V	1.05000	4.44	120.0	56.1	0.0	0.0	0.0	6	10	37.3	17.2
									9	11	82.7	38.9
6	L	0.97681	-2.50	0.0	0.0	70.0	30.0	0.0	4	7	-33.6	-18.3
									5	10	-36.4	-11.7
7	L	0.96662	-5.04	0.0	0.0	55.0	15.0	0.0	2	4	-49.5	-17.0
									8	12	5.8	7.6
									10	13	-11.3	-5.6
8	L	0.95261	-5.50	0.0	0.0	90.0	50.0	0.0	4	8	-51.9	-20.6
									7	12	-5.8	-7.4
									9	14	-14.6	-3.9
									10	15	-15.1	-10.3
									11	16	-2.6	-7.7
9	L	0.97798	-2.42	0.0	0.0	95.0	45.0	0.0	1	1	-10.5	-12.3
									4	9	-18.4	-10.7
									5	11	-80.8	-26.8
									8	14	14.7	4.8
10	L	0.98556	-3.54	0.0	0.0	35.0	7.0	0.0	2	5	-70.1	-25.4
									7	13	11.4	6.0
									8	15	15.3	11.2
									11	17	8.4	1.2
11	L	0.97664	-5.30	0.0	0.0	70.0	25.0	0.0	1	2	-64.2	-32.0
									8	16	2.6	7.9
									10	17	-8.4	-0.9
TOTALS				461.3	250.3	450.0	182.0	0.0				

Table 3.6 Power Flow Results for the 11 Bus System
(Imp. Version 2 EC Method)

```
* Power Flow Method :  Imp. Version 2 EC Method
* No. of Iterations :  4.5


*--  BUS DATA ---*  *GENERATION*  *---LOAD---*  *REAC*    *---  LINE FLOW   ---*
BS TY  VOLTS ANGLE     MW   MVAR    MW    MVAR    MVAR     TO LN    MW      MVAR

                                                          --------------------
 1 S 1.05000   0.00   76.3  54.3    0.0    0.0    0.0      9  1    10.7    13.7
                                                          11  2    65.6    40.6
                                                          --------------------
 2 V 1.05000   2.33  105.0  63.0    0.0    0.0    0.0      3  3   -17.5     3.3
                                                           7  4    51.0    25.1
                                                          10  5    71.5    34.5
                                                          --------------------
 3 V 1.05000   7.01   90.0   3.4   35.0   10.0    0.0      2  3    17.7    -1.9
                                                           4  6    37.3    -4.6
                                                          --------------------
 4 V 1.05000   2.26   70.0  73.4    0.0    0.0    0.0      3  6   -36.8     7.7
                                                           6  7    34.4    22.6
                                                           8  8    53.7    30.2
                                                           9  9    18.7    13.0
                                                          --------------------
 5 V 1.05000   4.44  120.0  56.1    0.0    0.0    0.0      6 10    37.3    17.2
                                                           9 11    82.7    38.9
                                                          --------------------
 6 L 0.97681  -2.50    0.0   0.0   70.0   30.0    0.0      4  7   -33.6   -18.3
                                                           5 10   -36.4   -11.7
                                                          --------------------
 7 L 0.96662  -5.04    0.0   0.0   55.0   15.0    0.0      2  4   -49.5   -17.0
                                                           8 12     5.8     7.6
                                                          10 13   -11.3    -5.6
                                                          --------------------
 8 L 0.95261  -5.50    0.0   0.0   90.0   50.0    0.0      4  8   -51.9   -20.6
                                                           7 12    -5.8    -7.4
                                                           9 14   -14.6    -3.9
                                                          10 15   -15.1   -10.3
                                                          11 16    -2.6    -7.7
                                                          --------------------
 9 L 0.97798  -2.42    0.0   0.0   95.0   45.0    0.0      1  1   -10.5   -12.3
                                                           4  9   -18.4   -10.7
                                                           5 11   -80.8   -26.8
                                                           8 14    14.7     4.8
                                                          --------------------
10 L 0.98556  -3.54    0.0   0.0   35.0    7.0    0.0      2  5   -70.1   -25.4
                                                           7 13    11.4     6.0
                                                           8 15    15.3    11.2
                                                          11 17     8.4     1.2
                                                          --------------------
11 L 0.97664  -5.30    0.0   0.0   70.0   25.0    0.0      1  2   -64.2   -32.0
                                                           8 16     2.6     7.9
                                                          10 17    -8.4    -0.9

                    ------------ ----- ------  -------
       TOTALS       461.3 250.3  450.0 182.0      0.0
```

Table 3.7 Power Flow Results for the 11 Bus System
(Epsilon Coupling Method)

```
* Power Flow Method :  EC Method
* No. of Iterations :  4.5

*-- BUS DATA ---*     *GENERATION*  *---LOAD---*  *REAC*    *---  LINE FLOW   ---*
BS TY  VOLTS ANGLE       MW   MVAR     MW   MVAR   MVAR     TO LN      MW     MVAR

 1 S 1.05000   0.00    76.3   54.3    0.0    0.0    0.0    --------------------
                                                           9  1      10.7   13.7
                                                          11  2      65.6   40.6
                                                          --------------------
 2 V 1.05000   2.33   105.0   63.0    0.0    0.0    0.0    3  3     -17.5    3.3
                                                           7  4      51.0   25.1
                                                          10  5      71.5   34.5
                                                          --------------------
 3 V 1.05000   7.01    90.0    3.4   35.0   10.0    0.0    2  3      17.7   -1.9
                                                           4  6      37.3   -4.6
                                                          --------------------
 4 V 1.05000   2.26    70.0   73.4    0.0    0.0    0.0    3  6     -36.8    7.7
                                                           6  7      34.4   22.6
                                                           8  8      53.7   30.2
                                                           9  9      18.7   13.0
                                                          --------------------
 5 V 1.05000   4.44   120.0   56.1    0.0    0.0    0.0    6 10      37.3   17.2
                                                           9 11      82.7   38.9
                                                          --------------------
 6 L 0.97681  -2.50     0.0    0.0   70.0   30.0    0.0    4  7     -33.6  -18.3
                                                           5 10     -36.4  -11.7
                                                          --------------------
 7 L 0.96662  -5.04     0.0    0.0   55.0   15.0    0.0    2  4     -49.5  -17.0
                                                           8 12       5.8    7.6
                                                          10 13     -11.3   -5.6
                                                          --------------------
 8 L 0.95261  -5.50     0.0    0.0   90.0   50.0    0.0    4  8     -51.9  -20.6
                                                           7 12      -5.8   -7.4
                                                           9 14     -14.6   -3.9
                                                          10 15     -15.1  -10.3
                                                          11 16      -2.6   -7.7
                                                          --------------------
 9 L 0.97798  -2.42     0.0    0.0   95.0   45.0    0.0    1  1     -10.5  -12.3
                                                           4  9     -18.4  -10.7
                                                           5 11     -80.8  -26.8
                                                           8 14      14.7    4.8
                                                          --------------------
10 L 0.98556  -3.54     0.0    0.0   35.0    7.0    0.0    2  5     -70.1  -25.4
                                                           7 13      11.4    6.0
                                                           8 15      15.3   11.2
                                                          11 17       8.4    1.2
                                                          --------------------
11 L 0.97664  -5.30     0.0    0.0   70.0   25.0    0.0    1  2     -64.2  -32.0
                                                           8 16       2.6    7.9
                                                          10 17      -8.4   -0.9

                    ------------ -----  ------   -------
         TOTALS    461.3  250.3  450.0  182.0      0.0
```

Table 3.8 Power Flow Results for the 11 Bus System
(Imp. FD Method)

* Power Flow Method : Imp. FD Method

* No. of Iterations : 4

-- BUS DATA ---				*GENERATION*		*---LOAD---*		*REAC*	*--- LINE FLOW ---*			
BS	TY	VOLTS	ANGLE	MW	MVAR	MW	MVAR	MVAR	TO	LN	MW	MVAR
1	S	1.05000	0.00	76.3	54.3	0.0	0.0	0.0	9 11	1 2	10.7 65.6	13.7 40.6
2	V	1.05000	2.33	105.0	63.0	0.0	0.0	0.0	3 7 10	3 4 5	-17.5 51.0 71.5	3.3 25.1 34.5
3	V	1.05000	7.01	90.0	3.4	35.0	10.0	0.0	2 4	3 6	17.7 37.3	-1.9 -4.6
4	V	1.05000	2.26	70.0	73.4	0.0	0.0	0.0	3 6 8 9	6 7 8 9	-36.8 34.4 53.7 18.7	7.7 22.6 30.2 13.0
5	V	1.05000	4.44	120.0	56.1	0.0	0.0	0.0	6 9	10 11	37.3 82.7	17.2 38.9
6	L	0.97681	-2.50	0.0	0.0	70.0	30.0	0.0	4 5	7 10	-33.6 -36.4	-18.3 -11.7
7	L	0.96662	-5.04	0.0	0.0	55.0	15.0	0.0	2 8 10	4 12 13	-49.5 5.8 -11.3	-17.0 7.6 -5.6
8	L	0.95261	-5.50	0.0	0.0	90.0	50.0	0.0	4 7 9 10 11	8 12 14 15 16	-51.9 -5.8 -14.6 -15.1 -2.6	-20.6 -7.4 -3.9 -10.3 -7.7
9	L	0.97798	-2.42	0.0	0.0	95.0	45.0	0.0	1 4 5 8	1 9 11 14	-10.5 -18.4 -80.8 14.7	-12.3 -10.7 -26.8 4.8
10	L	0.98556	-3.54	0.0	0.0	35.0	7.0	0.0	2 7 8 11	5 13 15 17	-70.1 11.4 15.3 8.4	-25.4 6.0 11.2 1.2
11	L	0.97664	-5.30	0.0	0.0	70.0	25.0	0.0	1 8 10	2 16 17	-64.2 2.6 -8.4	-32.0 7.9 -0.9
TOTALS				461.3	250.3	450.0	182.0	0.0				

Table 3.9 Power Flow Results for the 11 Bus System
(FD Method)

```
* Power Flow Method :  FD Method
* No. of Iterations :  3.5

*--  BUS DATA ---*  *GENERATION*  *---LOAD---*  *REAC*    *---  LINE FLOW   ---*
BS TY  VOLTS ANGLE     MW  MVAR      MW   MVAR    MVAR    TO LN      MW     MVAR

 1 S 1.05000   0.00   76.3  54.3    0.0    0.0    0.0
                                                         ----------------------
                                                          9  1     10.7   13.7
 2 V 1.05000   2.33  105.0  63.0    0.0    0.0    0.0    11  2     65.6   40.6
                                                         ----------------------
                                                          3  3    -17.5    3.3
                                                          7  4     51.0   25.1
 3 V 1.05000   7.01   90.0   3.4   35.0   10.0    0.0    10  5     71.5   34.5
                                                         ----------------------
                                                          2  3     17.7   -1.9
 4 V 1.05000   2.26   70.0  73.4    0.0    0.0    0.0     4  6     37.3   -4.6
                                                         ----------------------
                                                          3  6    -36.8    7.7
                                                          6  7     34.4   22.6
                                                          8  8     53.7   30.2
 5 V 1.05000   4.44  120.0  56.1    0.0    0.0    0.0     9  9     18.7   13.0
                                                         ----------------------
                                                          6 10     37.3   17.2
 6 L 0.97681  -2.50    0.0   0.0   70.0   30.0    0.0     9 11     82.7   38.9
                                                         ----------------------
                                                          4  7    -33.6  -18.3
 7 L 0.96663  -5.04    0.0   0.0   55.0   15.0    0.0     5 10    -36.4  -11.7
                                                         ----------------------
                                                          2  4    -49.5  -17.0
                                                          8 12      5.8    7.6
 8 L 0.95262  -5.50    0.0   0.0   90.0   50.0    0.0    10 13    -11.3   -5.6
                                                         ----------------------
                                                          4  8    -51.9  -20.6
                                                          7 12     -5.8   -7.4
                                                          9 14    -14.6   -3.9
                                                         10 15    -15.1  -10.3
 9 L 0.97798  -2.42    0.0   0.0   95.0   45.0    0.0    11 16     -2.6   -7.7
                                                         ----------------------
                                                          1  1    -10.5  -12.3
                                                          4  9    -18.4  -10.7
                                                          5 11    -80.8  -26.8
10 L 0.98556  -3.54    0.0   0.0   35.0    7.0    0.0     8 14     14.7    4.8
                                                         ----------------------
                                                          2  5    -70.1  -25.4
                                                          7 13     11.4    6.0
                                                          8 15     15.3   11.2
11 L 0.97665  -5.30    0.0   0.0   70.0   25.0    0.0    11 17      8.4    1.2
                                                         ----------------------
                                                          1  2    -64.2  -32.0
                                                          8 16      2.6    7.9
                                                         10 17     -8.4   -0.9
                     -----  -----  -----  -----  -----
             TOTALS  461.3  250.3  450.0  182.0    0.0
```

Table 3.10 System Data for the 39 Bus System

* Base	:	100.0 MVA	230.0 KV
* No. of Lines	:	47	
* No. of Generators	:	10	
* No. of Loads	:	17	

* T/L Data

NO.	FBS	TBS	R(%)	X(%)	MVAC	|YS|	GAM	|YP|
1	1	2	0.35	4.11	69.9	24.2	0.0	0.0
2	1	27	3.20	32.00	41.0	3.1	0.0	0.0
3	1	39	0.37	4.25	204.0	23.4	0.0	0.0
4	2	3	0.13	1.51	25.7	66.0	0.0	0.0
5	2	25	0.70	0.86	14.6	90.2	0.0	0.0
6	2	30	0.00	1.81	0.0	55.2	0.0	0.0
7	3	4	0.13	2.13	22.1	46.9	0.0	0.0
8	3	18	0.11	1.33	21.4	74.9	0.0	0.0
9	4	5	0.08	1.28	13.4	78.0	0.0	0.0
10	4	14	0.08	1.29	13.8	77.4	0.0	0.0
11	5	6	0.02	0.26	4.3	383.5	0.0	0.0
12	5	8	0.08	1.12	14.8	89.1	0.0	0.0
13	6	7	0.06	0.92	11.3	108.5	0.0	0.0
14	6	11	0.07	0.82	13.9	121.5	0.0	0.0
15	6	31	0.00	2.50	0.0	40.0	0.0	0.0
16	7	8	0.04	0.46	7.8	216.6	0.0	0.0
17	8	9	0.23	3.63	38.0	27.5	0.0	0.0
18	9	39	0.82	7.58	126.0	13.1	0.0	0.0
19	10	11	0.04	0.43	7.3	231.6	0.0	0.0
20	10	13	0.04	0.43	7.3	231.6	0.0	0.0
21	10	32	0.00	2.00	0.0	50.0	0.0	0.0
22	11	12	0.16	4.35	0.0	23.0	0.0	0.0
23	12	13	0.16	4.35	0.0	23.0	0.0	0.0
24	13	14	0.09	1.01	17.2	98.6	0.0	0.0
25	14	15	0.18	2.17	36.6	45.9	0.0	0.0
26	15	16	0.09	0.94	17.1	105.9	0.0	0.0
27	16	17	0.07	0.89	13.4	112.0	0.0	0.0
28	16	19	0.16	1.95	30.4	51.1	0.0	0.0
29	16	21	0.08	1.35	25.5	73.9	0.0	0.0
30	16	24	0.03	0.59	6.8	169.3	0.0	0.0
31	17	18	0.09	0.82	13.2	121.2	0.0	0.0
32	17	27	0.13	1.73	32.2	57.6	0.0	0.0
33	19	20	0.07	1.38	0.0	72.4	0.0	0.0
34	19	33	0.07	1.42	0.0	70.3	0.0	0.0
35	20	34	0.09	1.80	0.0	55.5	0.0	0.0
36	21	22	0.08	1.40	25.7	71.3	0.0	0.0
37	22	23	0.06	0.96	18.5	104.0	0.0	0.0
38	22	35	0.00	1.43	0.0	69.9	0.0	0.0
39	23	24	0.22	3.50	36.1	28.5	0.0	0.0
40	23	36	0.05	2.72	0.0	36.8	0.0	0.0
41	25	26	0.32	3.23	53.1	30.8	0.0	0.0
42	26	27	0.14	1.47	24.0	67.7	0.0	0.0
43	26	28	0.43	4.74	78.0	21.0	0.0	0.0
44	26	29	0.57	6.25	102.9	15.9	0.0	0.0
45	28	29	0.14	1.51	24.9	65.9	0.0	0.0
46	29	38	0.08	1.56	0.0	64.0	0.0	0.0
47	25	37	0.06	2.32	0.0	43.1	0.0	0.0

Table 3.10-continued

* Generation Data

GEN NO	BUS NO	BUS TYP	RATED CAP MVA	AVAILAB CAP MVA	CURRENT GENERAT.	
					MW	MVAR
1	30	V	500.0	500.0	280.0	
2	31	V	600.0	600.0	436.0	
3	32	V	700.0	700.0	440.0	
4	33	V	700.0	700.0	425.6	
5	34	V	550.0	550.0	404.2	
6	35	V	800.0	800.0	400.0	
7	36	V	600.0	600.0	368.0	
8	37	V	600.0	600.0	352.0	
9	38	V	800.0	800.0	400.0	
10	39	S	500.0	500.0	0.0	

* Load Data

LOAD NO.	BUS NO.	*LOAD CAPACITY*	
		MW	MVAR
1	3	257.6	41.6
2	4	200.0	67.2
3	7	147.2	43.2
4	8	101.6	37.6
5	12	87.2	46.4
6	15	176.0	42.4
7	16	263.2	105.6
8	18	126.4	64.0
9	20	464.0	122.4
10	21	299.2	132.0
11	23	198.4	68.0
12	24	247.2	8.0
13	25	179.2	117.6
14	26	270.4	93.6
15	27	224.8	60.8
16	28	204.8	102.4
17	29	227.2	101.6

Table 3.11 Power Flow Results for the 39 Bus System
(Full NR Method)

```
* Power Flow Method :  Full NR Method
* No. of Iterations :  6


*--  BUS DATA ---*    *GENERATION*  *---LOAD---*  *REAC*    *---  LINE FLOW   ---*
BS TY  VOLTS ANGLE      MW   MVAR     MW    MVAR    MVAR     TO LN       MW      MVAR

 1 L 1.07340  -2.54     0.0   0.0     0.0    0.0    0.0
                                                            ---------------------
                                                              2  1       93.3  54.8
                                                             27  2       43.8  -2.1
                                                             39  3     -137.0 -52.8
 2 L 1.03448  -4.35     0.0   0.0     0.0    0.0    0.0
                                                            ---------------------
                                                              1  1      -92.7-126.1
                                                              3  4      253.1 123.3
                                                             25  5      119.6  73.6
                                                             30  6     -280.0 -70.7
 3 L 1.01191  -6.34     0.0   0.0   257.6   41.6    0.0
                                                            ---------------------
                                                              2  4     -252.1-138.5
                                                              4  7     -165.9  52.9
                                                             18  8      160.4  44.0
 4 L 1.00116  -4.30     0.0   0.0   200.0   67.2    0.0
                                                            ---------------------
                                                              3  7      166.3 -68.7
                                                              5  9     -290.9 -11.2
                                                             14 10      -75.3  12.8
 5 L 1.00475  -2.18     0.0   0.0     0.0    0.0    0.0
                                                            ---------------------
                                                              4  9      291.6   8.5
                                                              6 11     -337.5  30.9
                                                              8 12       45.9 -39.5
 6 L 1.00460  -1.68     0.0   0.0     0.0    0.0    0.0
                                                            ---------------------
                                                              5 11      337.7 -32.4
                                                              7 13      149.9 -24.3
                                                             11 14      -51.6  67.0
                                                             31 15     -436.0 -10.3
 7 L 1.00550  -2.47     0.0   0.0   147.2   43.2    0.0
                                                            ---------------------
                                                              6 13     -149.7  14.9
                                                              8 16        2.5 -58.1
 8 L 1.00797  -2.48     0.0   0.0   101.6   37.6    0.0
                                                            ---------------------
                                                              5 12      -45.9  24.9
                                                              7 16       -2.5  50.3
                                                              9 17      -53.2-112.8
 9 L 1.04299  -1.55     0.0   0.0     0.0    0.0    0.0
                                                            ---------------------
                                                              8 17       53.5  76.9
                                                             39 18      -53.5 -76.9
10 L 0.99689  -1.13     0.0   0.0     0.0    0.0    0.0
                                                            ---------------------
                                                             11 19      106.5 -60.4
                                                             13 20      333.5 -33.6
                                                             32 21     -440.0  94.1
11 L 0.99893  -1.41     0.0   0.0     0.0    0.0    0.0
                                                            ---------------------
                                                              6 14       51.6 -80.2
                                                             10 19     -106.4  53.8
                                                             12 22       54.8  26.4
12 L 0.98682  -2.77     0.0   0.0    87.2   46.4    0.0
                                                            ---------------------
                                                             11 22      -54.7 -24.8
                                                             13 23      -32.5 -21.6
```

Table 3.11-continued

*-- BUS DATA			---*	*GENERATION*		*---LOAD---*		*REAC*	*--- LINE FLOW			---*
BS	TY	VOLTS	ANGLE	MW	MVAR	MW	MVAR	MVAR	TO	LN	MW	MVAR
13	L	0.99696	-1.96	0.0	0.0	0.0	0.0	0.0	10	20	-333.1	31.2
									12	23	32.5	22.3
									14	24	300.6	-53.5
14	L	0.99927	-3.73	0.0	0.0	0.0	0.0	0.0	4	10	75.4	-25.8
									13	24	-299.7	45.7
									15	25	224.4	-19.9
15	L	0.99677	-6.54	0.0	0.0	176.0	42.4	0.0	14	25	-223.5	-5.6
									16	26	47.5	-36.8
16	L	0.99902	-6.81	0.0	0.0	263.2	105.6	0.0	15	26	-47.4	20.0
									17	27	165.2	-57.1
									19	28	-360.7	51.5
									21	29	-79.6	-48.0
									24	30	59.4	-72.1
17	L	1.00247	-7.67	0.0	0.0	0.0	0.0	0.0	16	27	-165.0	46.3
									18	31	-33.7	-11.2
									27	32	198.7	-35.1
18	L	1.00314	-7.51	0.0	0.0	126.4	64.0	0.0	3	8	-160.1	-62.0
									17	31	33.7	-2.0
19	L	0.99435	-2.69	0.0	0.0	0.0	0.0	0.0	16	28	362.9	-55.4
									20	33	61.4	33.1
									33	34	-424.3	22.4
20	L	0.98937	-3.17	0.0	0.0	464.0	122.4	0.0	19	33	-61.4	-32.4
									34	35	-402.6	-90.0
21	L	1.00448	-6.21	0.0	0.0	299.2	132.0	0.0	16	29	79.7	23.5
									22	36	-378.9	-155.5
22	L	1.02866	-3.33	0.0	0.0	0.0	0.0	0.0	21	36	380.2	151.7
									23	37	19.8	-8.8
									35	38	-400.0	-142.9
23	L	1.02846	-3.43	0.0	0.0	198.4	68.0	0.0	22	37	-19.8	-10.7
									24	39	188.7	49.9
									36	40	-367.3	-107.2
24	L	1.00291	-7.02	0.0	0.0	247.2	8.0	0.0	16	30	-59.3	65.8
									23	39	-187.9	-73.8
25	L	1.01963	-4.60	0.0	0.0	179.2	117.6	0.0	2	5	-118.3	-87.3
									26	41	290.3	-3.0
									37	47	-351.3	-27.3
26	L	1.00685	-9.80	0.0	0.0	270.4	93.6	0.0	25	41	-287.7	-25.2
									27	42	-16.5	10.7
									28	43	41.7	-26.5
									29	44	-7.9	-52.6

Table 3.11-continued

```
*--  BUS DATA ---*  *GENERATION*  *---LOAD---*  *REAC*     *---  LINE FLOW   ---*
BS TY  VOLTS ANGLE     MW  MVAR     MW   MVAR    MVAR      TO LN      MW      MVAR

27 L 1.00375  -9.64   0.0   0.0  224.8   60.8     0.0
                                                           --------------------
                                                            1  2     -43.1 -35.6
                                                           17 32    -198.2   9.6
                                                           26 42      16.5 -34.8
28 L 0.99912 -10.89   0.0   0.0  204.8  102.4     0.0      --------------------
                                                           26 43     -41.6 -51.1
29 L 1.00757  -9.52   0.0   0.0  227.2  101.6     0.0      29 45    -163.2 -51.3
                                                           --------------------
                                                           26 44       7.9 -51.8
                                                           28 45     163.6  30.5
                                                           38 46    -398.7 -80.3
30 V 1.04800  -1.67 280.0  84.8    0.0    0.0     0.0      --------------------
                                                            2  6     280.0  84.8
31 V 1.01300   4.47 436.0  57.5    0.0    0.0     0.0      --------------------
                                                            6 15     436.0  57.5
32 V 0.98200   4.03 440.0 -53.3    0.0    0.0     0.0      --------------------
                                                           10 21     440.0 -53.3
33 V 0.99600   0.81 425.6   3.6    0.0    0.0     0.0      --------------------
                                                           19 34     425.6   3.6
34 V 1.01200   0.94 404.2 121.3    0.0    0.0     0.0      --------------------
                                                           20 35     404.2 121.3
35 V 1.05000  -0.29 400.0 167.3    0.0    0.0     0.0      --------------------
                                                           22 38     400.0 167.3
36 V 1.06300   1.78 368.0 144.9    0.0    0.0     0.0      --------------------
                                                           23 40     368.0 144.9
37 V 1.03100  -0.16 352.0  55.0    0.0    0.0     0.0      --------------------
                                                           25 47     352.0  55.0
38 V 1.02500  -6.10 400.0 105.8    0.0    0.0     0.0      --------------------
                                                           29 46     400.0 105.8
39 S 1.05400   0.53 191.5-229.1    0.0    0.0     0.0      --------------------
                                                            1  3     137.8-169.6
                                                            9 18      53.7 -59.5

                   ----------- ----- ------ ------   -------
           TOTALS  3697.3  457.7 3674.4 1254.4        0.0
```

Table 3.12 Power Flow Results for the 39 Bus System
(Decoupled NR Method)

```
* Power Flow Method :  Decoupled NR Method
* No. of Iterations :  6


*--  BUS DATA ---*  *GENERATION*  *---LOAD---*  *REAC*     *---  LINE FLOW   ---*
BS TY  VOLTS ANGLE     MW   MVAR     MW    MVAR    MVAR     TO LN     MW      MVAR

 1 L 1.07340  -2.54    0.0    0.0    0.0    0.0     0.0     --------------------
                                                             2  1     93.3   54.8
                                                            27  2     43.8   -2.1
 2 L 1.03448  -4.35    0.0    0.0    0.0    0.0     0.0     39  3   -137.0  -52.8
                                                            --------------------
                                                             1  1    -92.7-126.1
                                                             3  4    253.1  123.3
                                                            25  5    119.6   73.6
 6 L 1.00460  -1.68    0.0    0.0    0.0    0.0     0.0     30  6   -280.0  -70.7
                                                            --------------------
                                                             5 11    337.7  -32.4
                                                             7 13    149.9  -24.3
                                                            11 14    -51.6   67.0
10 L 0.99689  -1.13    0.0    0.0    0.0    0.0     0.0     31 15   -436.0  -10.3
                                                            --------------------
                                                            11 19    106.5  -60.4
                                                            13 20    333.5  -33.6
11 L 0.99893  -1.41    0.0    0.0    0.0    0.0     0.0     32 21   -440.0   94.1
                                                            --------------------
                                                             6 14     51.6  -80.2
                                                            10 19   -106.4   53.8
15 L 0.99677  -6.54    0.0    0.0  176.0   42.4     0.0     12 22     54.8   26.4
                                                            --------------------
                                                            14 25   -223.5   -5.6
16 L 0.99902  -6.81    0.0    0.0  263.2  105.6     0.0     16 26     47.5  -36.8
                                                            --------------------
                                                            15 26    -47.4   20.0
                                                            17 27    165.2  -57.1
                                                            19 28   -360.7   51.5
                                                            21 29    -79.6  -48.0
20 L 0.98937  -3.17    0.0    0.0  464.0  122.4     0.0     24 30     59.4  -72.1
                                                            --------------------
                                                            19 33    -61.4  -32.4
24 L 1.00291  -7.02    0.0    0.0  247.2    8.0     0.0     34 35   -402.6  -90.0
                                                            --------------------
                                                            16 30    -59.3   65.8
25 L 1.01963  -4.60    0.0    0.0  179.2  117.6     0.0     23 39   -187.9  -73.8
                                                            --------------------
                                                             2  5   -118.3  -87.3
                                                            26 41    290.3   -3.0
31 V 1.01300   4.47  436.0   57.5    0.0    0.0     0.0     37 47   -351.3  -27.3
                                                            --------------------
39 S 1.05400   0.53  191.5-229.1     0.0    0.0     0.0      6 15    436.0   57.5
                                                            --------------------
                                                             1  3    137.8-169.6
                                                             9 18     53.7  -59.5
```

Table 3.13 Power Flow Results for the 39 Bus System
(Accelerated DC NR Method)

```
* Power Flow Method :   Accelerated DC NR Method
* No. of Iterations :   6


*--  BUS DATA ---*  *GENERATION*  *---LOAD---*  *REAC*      *---  LINE FLOW   ---*
BS TY  VOLTS ANGLE     MW   MVAR     MW    MVAR   MVAR       TO LN      MW     MVAR
  1 L 1.07340  -2.54   0.0   0.0     0.0    0.0    0.0
                                                           --------------------------
                                                             2  1       93.3   54.8
                                                            27  2       43.8   -2.1
                                                            39  3     -137.0  -52.8
  2 L 1.03448  -4.35   0.0   0.0     0.0    0.0    0.0
                                                           --------------------------
                                                             1  1      -92.7-126.1
                                                             3  4      253.1  123.3
                                                            25  5      119.6   73.6
                                                            30  6     -280.0  -70.7
  6 L 1.00460  -1.68   0.0   0.0     0.0    0.0    0.0
                                                           --------------------------
                                                             5 11      337.7  -32.4
                                                             7 13      149.9  -24.3
                                                            11 14      -51.6   67.0
                                                            31 15     -436.0  -10.3
 10 L 0.99689  -1.13   0.0   0.0     0.0    0.0    0.0
                                                           --------------------------
                                                            11 19      106.5  -60.4
                                                            13 20      333.5  -33.6
                                                            32 21     -440.0   94.1
 11 L 0.99893  -1.41   0.0   0.0     0.0    0.0    0.0
                                                           --------------------------
                                                             6 14       51.6  -80.2
                                                            10 19     -106.4   53.8
                                                            12 22       54.8   26.4
 15 L 0.99677  -6.54   0.0   0.0   176.0   42.4    0.0
                                                           --------------------------
                                                            14 25     -223.5   -5.6
                                                            16 26       47.5  -36.8
 16 L 0.99902  -6.81   0.0   0.0   263.2  105.6    0.0
                                                           --------------------------
                                                            15 26      -47.4   20.0
                                                            17 27      165.2  -57.1
                                                            19 28     -360.7   51.5
                                                            21 29      -79.6  -48.0
                                                            24 30       59.4  -72.1
 20 L 0.98937  -3.17   0.0   0.0   464.0  122.4    0.0
                                                           --------------------------
                                                            19 33      -61.4  -32.4
                                                            34 35     -402.6  -90.0
 24 L 1.00291  -7.02   0.0   0.0   247.2    8.0    0.0
                                                           --------------------------
                                                            16 30      -59.3   65.8
                                                            23 39     -187.9  -73.8
 25 L 1.01963  -4.60   0.0   0.0   179.2  117.6    0.0
                                                           --------------------------
                                                             2  5     -118.3  -87.3
                                                            26 41      290.3   -3.0
                                                            37 47     -351.3  -27.3
 31 V 1.01300   4.47 436.0  57.5     0.0    0.0    0.0
                                                           --------------------------
                                                             6 15      436.0   57.5
 39 S 1.05400   0.53 191.5-229.1     0.0    0.0    0.0
                                                           --------------------------
                                                             1  3      137.8-169.6
                                                             9 18       53.7  -59.5
```

Table 3.14 Power Flow Results for the 39 Bus System
(Imp. Version 1 EC Method)

```
* Power Flow Method :  Imp. Version 1 EC Method
* No. of Iterations :  6

*--  BUS DATA ---*  *GENERATION*  *---LOAD---*  *REAC*    *---  LINE FLOW    ---*
BS TY  VOLTS ANGLE    MW   MVAR     MW    MVAR    MVAR     TO LN     MW      MVAR

 1 L 1.07341  -2.54    0.0   0.0     0.0    0.0     0.0    -----------------------
                                                            2  1        93.3   54.8
                                                           27  2        43.8   -2.1
                                                           39  3      -137.0  -52.8
 2 L 1.03448  -4.35    0.0   0.0     0.0    0.0     0.0    -----------------------
                                                            1  1       -92.7-126.1
                                                            3  4       253.1  123.3
                                                           25  5       119.6   73.6
 6 L 1.00460  -1.68    0.0   0.0     0.0    0.0     0.0    30  6      -280.0  -70.7
                                                           -----------------------
                                                            5 11       337.7  -32.4
                                                            7 13       149.9  -24.3
                                                           11 14       -51.6   67.0
10 L 0.99690  -1.13    0.0   0.0     0.0    0.0     0.0    31 15      -436.0  -10.3
                                                           -----------------------
                                                           11 19       106.5  -60.4
                                                           13 20       333.5  -33.6
11 L 0.99893  -1.40    0.0   0.0     0.0    0.0     0.0    32 21      -440.0   94.1
                                                           -----------------------
                                                            6 14        51.6  -80.2
                                                           10 19      -106.4   53.8
15 L 0.99677  -6.53    0.0   0.0   176.0   42.4     0.0    12 22        54.8   26.4
                                                           -----------------------
                                                           14 25      -223.4   -5.6
16 L 0.99902  -6.81    0.0   0.0   263.2  105.6     0.0    16 26        47.4  -36.8
                                                           -----------------------
                                                           15 26       -47.4   20.0
                                                           17 27       165.3  -57.1
                                                           19 28      -360.8   51.5
                                                           21 29       -79.6  -48.0
20 L 0.98937  -3.16    0.0   0.0   464.0  122.4     0.0    24 30        59.4  -72.1
                                                           -----------------------
                                                           19 33       -61.4  -32.4
25 L 1.01963  -4.60    0.0   0.0   179.2  117.6     0.0    34 35      -402.6  -90.0
                                                           -----------------------
                                                            2  5      -118.3  -87.3
                                                           26 41       290.3   -3.0
31 V 1.01300   4.47  436.0  57.5     0.0    0.0     0.0    37 47      -351.3  -27.3
                                                           -----------------------
39 S 1.05400   0.53  191.5-229.1     0.0    0.0     0.0     6 15       436.0   57.5
                                                           -----------------------
                                                            1  3       137.8-169.6
                                                            9 18        53.7  -59.5
```

Table 3.15 Power Flow Results for the 39 Bus System
(Imp. Version 2 EC Method)

```
* Power Flow Method :  Imp. Version 2 EC Method
* No. of Iterations :  7.5

*-- BUS DATA ---* *GENERATION* *---LOAD---* *REAC*   *---  LINE FLOW   ---*
BS TY  VOLTS ANGLE    MW  MVAR     MW   MVAR  MVAR   TO LN      MW      MVAR

 1 L 1.07340 -2.54   0.0   0.0    0.0    0.0   0.0   ----------------------
                                                      2  1      93.3   54.8
                                                     27  2      43.8   -2.1
                                                     39  3    -137.0  -52.8
 2 L 1.03448 -4.35   0.1  -0.1    0.0    0.0   0.0   ----------------------
                                                      1  1     -92.7-126.1
                                                      3  4     253.1  123.3
                                                     25  5     119.8   73.5
                                                     30  6    -280.0  -70.7
 6 L 1.00460 -1.68   0.0   0.0    0.0    0.0   0.0   ----------------------
                                                      5 11     337.7  -32.4
                                                      7 13     149.9  -24.2
                                                     11 14     -51.6   67.0
                                                     31 15    -436.0  -10.4
10 L 0.99689 -1.13   0.0   0.0    0.0    0.0   0.0   ----------------------
                                                     11 19     106.5  -60.4
                                                     13 20     333.5  -33.6
                                                     32 21    -440.0   94.1
11 L 0.99893 -1.41   0.0   0.0    0.0    0.0   0.0   ----------------------
                                                      6 14      51.6  -80.2
                                                     10 19    -106.4   53.8
                                                     12 22      54.8   26.4
15 L 0.99677 -6.54   0.0   0.0  176.0   42.4   0.0   ----------------------
                                                     14 25    -223.5   -5.6
                                                     16 26      47.5  -36.8
16 L 0.99902 -6.81   0.0   0.0  263.2  105.6   0.0   ----------------------
                                                     15 26     -47.4   20.0
                                                     17 27     165.2  -57.1
                                                     19 28    -360.7   51.5
                                                     21 29     -79.6  -48.0
                                                     24 30      59.4  -72.1
20 L 0.98937 -3.17   0.0   0.0  464.0  122.4   0.0   ----------------------
                                                     19 33     -61.4  -32.4
                                                     34 35    -402.6  -90.0
24 L 1.00291 -7.02   0.0   0.0  247.2    8.0   0.0   ----------------------
                                                     16 30     -59.3   65.8
                                                     23 39    -187.9  -73.8
25 L 1.01962 -4.60  -0.1   0.1  179.2  117.6   0.0   ----------------------
                                                      2  5    -118.4  -87.2
                                                     26 41     290.3   -3.0
                                                     37 47    -351.3  -27.3
31 V 1.01300  4.47 436.0  57.5    0.0    0.0   0.0   ----------------------
                                                      6 15     436.0   57.5
39 S 1.05400  0.53 191.5-229.1    0.0    0.0   0.0   ----------------------
                                                      1  3     137.8-169.6
                                                      9 18      53.7  -59.5
```

Table 3.16 Power Flow Results for the 39 Bus System
(Epsilon Coupling Method)

```
* Power Flow Method :  EC Method
* No. of Iterations :  7.5

*--  BUS DATA ---*  *GENERATION*  *---LOAD---* *REAC*      *---  LINE FLOW   ---*
BS TY  VOLTS ANGLE     MW  MVAR      MW   MVAR   MVAR       TO LN     MW       MVAR

 1 L 1.07340  -2.54   0.0   0.0     0.0    0.0    0.0
                                                           --------------------
                                                            2  1      93.3   54.8
                                                           27  2      43.8   -2.1
 2 L 1.03448  -4.35  -0.1   0.1     0.0    0.0    0.0      39  3    -137.0  -52.8
                                                           --------------------
                                                            1  1     -92.7-126.1
                                                            3  4     253.1 123.3
                                                           25  5     119.5   73.7
 6 L 1.00460  -1.68   0.0   0.0     0.0    0.0    0.0      30  6    -280.0  -70.7
                                                           --------------------
                                                            5 11     337.7  -32.4
                                                            7 13     149.8  -24.2
                                                           11 14     -51.6   67.0
10 L 0.99689  -1.13   0.0   0.0     0.0    0.0    0.0      31 15    -436.0  -10.4
                                                           --------------------
                                                           11 19     106.5  -60.4
                                                           13 20     333.5  -33.6
11 L 0.99893  -1.41   0.0   0.0     0.0    0.0    0.0      32 21    -440.0   94.1
                                                           --------------------
                                                            6 14      51.6  -80.2
                                                           10 19    -106.4   53.8
15 L 0.99677  -6.54   0.0   0.0   176.0   42.4    0.0      12 22      54.8   26.4
                                                           --------------------
                                                           14 25    -223.4   -5.6
16 L 0.99902  -6.81   0.0   0.0   263.2  105.6    0.0      16 26      47.4  -36.8
                                                           --------------------
                                                           15 26     -47.4   20.0
                                                           17 27     165.2  -57.1
                                                           19 28    -360.7   51.5
                                                           21 29     -79.6  -48.0
20 L 0.98937  -3.17   0.0   0.0   464.0  122.4    0.0      24 30      59.4  -72.1
                                                           --------------------
                                                           19 33     -61.4  -32.4
24 L 1.00291  -7.02   0.0   0.0   247.2    8.0    0.0      34 35    -402.6  -90.0
                                                           --------------------
                                                           16 30     -59.3   65.8
25 L 1.01962  -4.60   0.1  -0.1   179.2  117.6    0.0      23 39    -187.9  -73.8
                                                           --------------------
                                                            2  5    -118.1  -87.4
                                                           26 41     290.4   -3.0
31 V 1.01300   4.47 436.0  57.5     0.0    0.0    0.0      37 47    -351.3  -27.3
                                                           --------------------
39 S 1.05400   0.53 191.5-229.1     0.0    0.0    0.0       6 15     436.0   57.5
                                                           --------------------
                                                            1  3     137.8-169.6
                                                            9 18      53.7  -59.5
```

Table 3.17 Power Flow Results for the 39 Bus System
(Imp. FD Method)

```
* Power Flow Method :  Imp. FD Method
* No. of Iterations :  6.5


*--  BUS DATA ---*   *GENERATION*  *---LOAD---*  *REAC*     *---  LINE FLOW   ---*
BS TY  VOLTS ANGLE      MW  MVAR     MW   MVAR    MVAR      TO LN     MW      MVAR

 1 L 1.07340  -2.54    0.0   0.0    0.0    0.0     0.0     ---------------------
                                                            2  1        93.3  54.8
                                                           27  2        43.8  -2.1
 2 L 1.03447  -4.35   -0.1   0.0    0.0    0.0     0.0     39  3      -137.0 -52.8
                                                           ---------------------
                                                            1  1       -92.7-126.1
                                                            3  4       253.1 123.3
                                                           25  5       119.5  73.6
 6 L 1.00460  -1.68    0.0   0.0    0.0    0.0     0.0     30  6      -280.0 -70.8
                                                           ---------------------
                                                            5 11       337.7 -32.4
                                                            7 13       149.9 -24.2
                                                           11 14       -51.6  67.0
10 L 0.99689  -1.13    0.0   0.0    0.0    0.0     0.0     31 15      -436.0 -10.4
                                                           ---------------------
                                                           11 19       106.5 -60.4
                                                           13 20       333.5 -33.6
11 L 0.99893  -1.41    0.0   0.0    0.0    0.0     0.0     32 21      -440.0  94.1
                                                           ---------------------
                                                            6 14        51.6 -80.2
                                                           10 19      -106.4  53.8
15 L 0.99677  -6.54    0.0   0.0  176.0   42.4     0.0     12 22        54.8  26.4
                                                           ---------------------
                                                           14 25      -223.4  -5.6
16 L 0.99902  -6.81    0.0   0.0  263.2  105.6     0.0     16 26        47.4 -36.8
                                                           ---------------------
                                                           15 26       -47.4  20.0
                                                           17 27       165.2 -57.1
                                                           19 28      -360.7  51.5
                                                           21 29       -79.6 -48.0
20 L 0.98937  -3.17    0.0   0.0  464.0  122.4     0.0     24 30        59.4 -72.1
                                                           ---------------------
                                                           19 33       -61.4 -32.4
24 L 1.00291  -7.02    0.0   0.0  247.2    8.0     0.0     34 35      -402.6 -90.0
                                                           ---------------------
                                                           16 30       -59.3  65.8
25 L 1.01963  -4.60    0.1   0.0  179.2  117.6     0.0     23 39      -187.9 -73.8
                                                           ---------------------
                                                            2  5      -118.1 -87.3
                                                           26 41       290.4  -3.0
31 V 1.01300   4.47  436.0  57.5    0.0    0.0     0.0     37 47      -351.3 -27.3
                                                           ---------------------
39 S 1.05400   0.53  191.5-229.1    0.0    0.0     0.0      6 15       436.0  57.5
                                                           ---------------------
                                                            1  3       137.8-169.6
                                                            9 18        53.7 -59.5
```

Table 3.18 Power Flow Results for the 39 Bus System
(FD Method)

```
* Power Flow Method :  FD Method

* No. of Iterations :  6.5


*--  BUS DATA ---*  *GENERATION*  *---LOAD---*  *REAC*      *---  LINE FLOW   ---*
BS TY  VOLTS ANGLE     MW  MVAR      MW   MVAR   MVAR       TO LN      MW      MVAR

 1 L 1.07340  -2.54    0.0   0.0    0.0    0.0    0.0       --------------------
                                                             2  1      93.3   54.8
                                                            27  2      43.8   -2.1
                                                            39  3    -137.0  -52.8
 2 L 1.03447  -4.35   -0.1   0.0    0.0    0.0    0.0       --------------------
                                                             1  1     -92.7-126.1
                                                             3  4     253.1  123.3
                                                            25  5     119.5   73.6
                                                            30  6    -280.0  -70.8
 6 L 1.00460  -1.68    0.0   0.0    0.0    0.0    0.0       --------------------
                                                             5 11     337.7  -32.4
                                                             7 13     149.8  -24.2
                                                            11 14     -51.6   67.0
                                                            31 15    -436.0  -10.4
10 L 0.99689  -1.13    0.0   0.0    0.0    0.0    0.0       --------------------
                                                            11 19     106.5  -60.4
                                                            13 20     333.5  -33.6
                                                            32 21    -440.0   94.1
11 L 0.99893  -1.41    0.0   0.0    0.0    0.0    0.0       --------------------
                                                             6 14      51.6  -80.2
                                                            10 19    -106.4   53.8
                                                            12 22      54.8   26.4
15 L 0.99677  -6.54    0.0   0.0  176.0   42.4    0.0       --------------------
                                                            14 25    -223.4   -5.6
                                                            16 26      47.4  -36.8
16 L 0.99902  -6.81    0.0   0.0  263.2  105.6    0.0       --------------------
                                                            15 26     -47.4   20.0
                                                            17 27     165.2  -57.1
                                                            19 28    -360.7   51.5
                                                            21 29     -79.6  -48.0
                                                            24 30      59.4  -72.1
20 L 0.98937  -3.17    0.0   0.0  464.0  122.4    0.0       --------------------
                                                            19 33     -61.4  -32.4
                                                            34 35    -402.6  -90.0
24 L 1.00291  -7.02    0.0   0.0  247.2    8.0    0.0       --------------------
                                                            16 30     -59.3   65.8
                                                            23 39    -187.9  -73.8
25 L 1.01963  -4.60    0.1   0.0  179.2  117.6    0.0       --------------------
                                                             2  5    -118.1  -87.3
                                                            26 41     290.4   -3.0
                                                            37 47    -351.3  -27.3
31 V 1.01300   4.47  436.0  57.5    0.0    0.0    0.0       --------------------
                                                             6 15     436.0   57.5
39 S 1.05400   0.53  191.5-229.1    0.0    0.0    0.0       --------------------
                                                             1  3     137.8-169.6
                                                             9 18      53.7  -59.5
```

R/X (AVG.)	** MAX. EIGEN VALUE	NUMBER	OF	REQUIRED				ITERATIONS	
		NR	DC NR	ACC NR	IMP V-1 EC	IMP V-2 EC	EC	IMP FD	FD
0.17	-0.025	5	4	4	4	4	4	4	3
0.23	-0.064	5	5	5	5	5	5	4	4
0.32	-0.126	6	6	6	6	7	6	6	7
0.40	-0.212	8	8	8	7	9	8	8	12
0.50	-0.318	10	10	10	11	*	*	11	*
0.60	-0.442	17	17	17	15	*	*	15	*

* : Power flow was not converged.
** : Max. Eigenvalue of $(L^{-1}UH^{-1})K$

Table 3.19 Effect of R/X Ratio Changes on the Convergence Characteristics (11 Bus System)

CHAPTER 4
NEW SENSITIVITY ANALYSIS METHODS

The Jacobian matrices obtained from the power flow calculations include the sensitivity information of the system state with respect to the changes in the bus injected power mismatches. Therefore, the advantage of the Jacobian based sensitivity methods over the other sensitivity methods is that it can fully utilize the readily available information with only trivial additional computations. In actual system operation, this is especially important since a large number of sensitivity analyses must be performed in a relatively short period of time. Sometimes accuracy of the results can be sacrificed as long as the sensitivity results does not mislead the operator or the planner to make a wrong decision.

As a result of the derivation of the GPF algorithm, several new sensitivity methods which can give gradual changes in the accuracy of the sensitivity solutions can be developed. Depending upon the power system operating configuration, the best compromise which can satisfy both requirements, such as the solution speed in the power flow calculation and the solution accuracy in the sensitivity analysis, can be selected.

4.1 Derivation

From the results of the GPF derivation in Chapter 3, both the state update vectors, ΔX_1 and ΔX_2, can be expressed as follows:

$$\begin{bmatrix} \Delta X_2 \\ \Delta X_1 \end{bmatrix} = \begin{bmatrix} S_{2p} & S_{2q} & 0 \\ H^{-1} & S_{1q} & S_{12} \end{bmatrix} \begin{bmatrix} \Delta P \\ \Delta Q \\ \Delta X_2 \end{bmatrix} = S_0 \begin{bmatrix} \Delta P \\ \Delta Q \\ \Delta X_2 \end{bmatrix} \qquad \text{--- (4.1)}$$

where S_{2p}, S_{2q}, S_{1q} and S_0 are the sensitivity matrices whose expressions vary according to each power flow method selected to solve the base case power flow. Expressions of these sensitivity matrices are summarized in Table (4.1). For example, in case of Improved version 2 of the EC method,

$$\begin{aligned} S_{2p} &= -L^{-1}JH \\ S_{2q} &= L^{-1} \\ S_{1q} &= 0 \\ S_{12} &= -H^{-1}K \end{aligned}$$

where S_{12} is invariant for all sensitivity methods except the FD and the EC methods, in which case S_{12} becomes zero.

Power mismatch ΔP and ΔQ in Eq. (4.1) are formulated to include the three different types of contingency -- loss of line, transformer or compensator, loss of generator or generation redispatching, and loss of load or load management. They can be expressed as follows to include all types of contingencies.

COMMON EXPRESS.	SENSITIVITY MATRICES FOR EACH METHOD					
	DC & ACC NR NR	IMP V-1 EC	IMP V-2 EC	EC	IMP FD	FD
S_{2p}	$-(I-AK)^{-1}A$	$-(I+AK)A$	$-A$	$-A$	0	0
S_{2q}	$(I-AK)^{-1}L^{-1}$	$(I+AK)L^{-1}$	L^{-1}	L^{-1}	L^{-1}	L^{-1}
S_{iq}	0	0	0	$-B$	0	0
S_{12}	$-HK^{-1}$	$-HK^{-1}$	$-HK^{-1}$	0	$-HK^{-1}$	0

$A : L^{-1}JH^{-1}$

$B : H^{-1}KL^{-1}$

Table 4.1 Sensitivity Matrices for the GPF Sensitivity Methods

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} \Delta P_G \\ \Delta P_G \end{bmatrix} + \begin{bmatrix} \Delta P_D \\ \Delta Q_D \end{bmatrix} + A \begin{bmatrix} P_{pq} \\ Q_{pq} \end{bmatrix} \qquad \text{---(4.2)}$$

where

ΔP_G : vector of real injected power changes caused by generator drops or generation redispatching

ΔQ_G : vector of reactive injected power changes caused by generator drops or generation redispatching

ΔP_D : vector of real injected power changes caused by load sheddings or load management

ΔQ_D : vector of reactive injective power changes caused by load sheddings or load management

P_{pq} : vector of base case real power flow

Q_{pq} : vector of base case reactive power flow

A : bus and transmission line(T/L) incidence matrix having one´s only for lines being removed

If any contingency occurs during the normal operating state, power mismatches on the corresponding buses would change. Then the state update vector can be quickly approximated using Eq. (4.1). Therefore, S_o is an overall sensitivity matrix around the solution point.

Except for the FD sensitivity method, in which case S_{12} becomes zero, all the expressions of Eq. (4.1) for other sensitivity methods include some forms of nonzero off-diagonal approximation terms. Since iterations are usually not performed in the sensitivity analysis, totally ignoring the off-diagonal terms, as is done in the FD method, sometimes creates large errors. Especially when the system is heavily loaded or it has several lines with high R/X ratio, the accuracy often becomes so poor that the solution is almost not acceptable for practical use. Thus, the way how to enhance the solution accuracy efficiently is essential in the sensitivity analysis. With the development of the GPF, several sensitivity matrices with different accuracy level become available.

4.2 Coupling between Power and Voltage

Historically, planners and operators have exploited the lack of coupling between real power and voltage magnitudes and to a lesser degree the coupling between reactive power and voltage angles. The reason for the lack of coupling was primarily due to the relatively low load levels compared to system capacity, and due to the prevailing transmission voltage levels. Economics has forced utilities nationwide to plan and operate systems closer to their thermal limits and to push towards higher and higher transmission voltages which has altered the coupling between the system states.

To understand what is happening to the coupling between real power and system voltages, it is only necessary to examine the elements of the submatrices J and K. For example, a typical element in K has the following form:

$$\frac{\partial P}{\partial V} = \frac{V}{X} \operatorname{Sin} \delta \qquad \text{---(4.3)}$$

From this simple expression it is clear that the more heavily loaded a system (and hence, the larger δ), the greater is the coupling between P and V. To put this into perspective, it can be shown that

$$\frac{\partial P}{\partial V} = \frac{\tan \delta}{V} \frac{\partial P}{\partial \delta} \qquad \text{----(4.4)}$$

For power angle near 45^{0} and unity voltages, the coupling between P and V is equal to the coupling between P and δ. Furthermore, as voltage collapses in a system, the coupling gets greater. This is unfortunate since contingencies that tend to severely degrade system voltages also dramatically upset the power balance, and hence, system frequency and stability.

A similar situation exists for reactive power and voltage angles where the coupling increases significantly with increasing voltage. Interpreted properly this means that the higher voltages incurred during the off-peak periods cause frequency and stability problems in the event of EHV line or compensator failures.

The purpose of this discussion is to emphasize the importance of retaining the off-diagonal coupling information in any voltage estimating contingency analysis. Although the NR method contains all the coupling information needed, it is computionally expensive to get. On the other hand, the FD method which is superior to the NR method in the solution speed produces poor information for obtaining voltage estimate, since the coupling information is ignored. The solution to this problem is to use the GPF model, which can give much freedom in the choice of power flow method and the subsequent sensitivity analysis.

4.3 Necessary Modification of the Sensitivity Analysis Methods

Some types of contingencies, like a line outage or a generator drop, require the appropriate modification in the sensitivity matrices. Line outages create changes in the system structure. Thus the related elements in the Jacobian should be modified. For generator outages, the bus type should be changed into load buses. Since only a couple of elements at specific location in the original Jacobian are subject to change for each contingency, the inverse of the new Jacobian can be obtained from the original inverse without repeating the time intensive matrix inversion process again.

4.3.1 Line outages

Different from other contingencies, entire line outage between two buses creates a structural change of the system. Then, the appropriate Ybus elements and the power mismatch equations, together with the subsequent Jacobian, should be modified accordingly.

If a transmission line connecting buses p and q is tripped, four elements, h_{pp}, h_{pq}, h_{qp} and h_{qq} should be changed in H, where h_{ij} is the ijth element of H. Hence,

$$\hat{H} = H + \Delta H \qquad ---(4.5)$$

where

$\hat{H}, \hat{L}, \hat{K}, \hat{J}$: modified H, L, K and J respectively, reflecting the changes in the system structure caused by the line outage.

ΔH : N x N matrix having only 4 non-zero elements at the location pp, pq, qp and qq, respectively.

Four non-zero elements in ΔH can be obtained from H such as

$$\begin{aligned} \Delta h_{pp} &= -\Delta h_{pq} = h_{pq} \triangleq \alpha \\ \Delta h_{qq} &= -\Delta h_{qp} = h_{qP} \triangleq \beta \end{aligned} \qquad ---(4.6)$$

where h_{ij} is the ij th element of H and can be easily computed using the base case power flow solution values as follows:

$$h_{ij} = \frac{\partial Fp}{\partial \delta j} = |Vi||Vj||Yij|\sin(\delta j - \delta i + \gamma ij) \qquad ---(4.7)$$

Multiplying H^{-1} on both sides of Eq. (4.5)

$$H^{-1}\hat{H} = I + H^{-1}\Delta H$$

Hence,

$$\hat{H} = H(I + H^{-1}\Delta H) \triangleq H(I + M) \qquad ---(4.8)$$

Inverting both sides of Eq. (4-16),

$$\hat{H}^{-1} = (I + M)^{-1}H^{-1} \triangleq T\,H^{-1} \qquad ---(4.9)$$

Here T can be considered as a transformation matrix of H^{-1} into $\hat{H}^{-1}$, and M is a matrix having only two non-zero columns, column p and q, which can be obtained from Eq.

(4.6), (4,7) and (4.8) such as

$$m_{iq} = -m_{ip}$$
$$m_{ip} = \bar{h}_{ip}\alpha - \bar{h}_{iq}\beta \qquad i = 1.....N \qquad \text{---}(4.10)$$

where

m_{ij} : ijth element of M

$\bar{h}_{ij}$: ijth element of H^{-1}

Because of the simple structure of matrix (I + M), T is identical with the identity matrix except two columns, p and q, whose elements can be expressed as

$$t_{ip} = \frac{-m_{ip}}{\gamma} \qquad \text{for } i \neq p$$
$$t_{iq} = -t_{ip}$$
$$t_{pp} = \frac{1 + m_{qq}}{\gamma}$$
$$t_{qq} = \frac{1 + m_{pp}}{\gamma} \qquad \text{---}(4.11)$$

where

$$\gamma = m_{pp} + m_{qq} + 1$$

The modified L^{-1}, $\hat{L}^{-1}$, can be obtained in a similar way except that t_{ij} for a voltage control bus need not be computed. Again ℓ_{ij}, the ijth element of L, can be computed as follows:

$$\ell_{ij} = \frac{\partial Fqi}{\partial Vj} = |Vi||Yij|\sin(\delta j - \delta i + \gamma ij) \qquad \text{---}(4.12)$$

For several line outages, the above procedure can be applied successively such as

$$\hat{H}^{-1} = T_n T_{n-1} \cdots T_1 H^{-1} \qquad \text{---(4.13)}$$

where

n: total number of line outages.

If the conductance of the nodal admittance of the faulted line is ignored, α can be put as equal to β in Eq. (4.6) and Eq. (4.7) for further simplification. Similarly $\hat{K}$ and $\hat{J}$ can be obtained from K and J by changing only four elements respectively, where the ijth element of K and J can be espressed as

$$k_{ij} = \frac{\partial Fpi}{\partial Vj} = -|Vi||Yij|\cos(\delta i - \delta j + \gamma ij) \qquad \text{---(4.14)}$$

$$j_{ij} = \frac{\partial Fqi}{\partial \delta j} = |Vi||Yij|\cos(\delta i - \delta j + \gamma ij) \qquad \text{---(4.15)}$$

Therefore from the Eq. (4.1) and the above derivation of the modified Jacobian submatrices, state update vector $\Delta X1$ and $\Delta X2$ can be computed from

$$\begin{bmatrix} \Delta X2 \\ \Delta X1 \end{bmatrix} = \begin{bmatrix} \hat{S}_{2p} & \hat{S}_{2q} & 0 \\ H & S_{1q} & \hat{S}_{12} \end{bmatrix} \begin{bmatrix} \Delta P \\ \Delta Q \\ \Delta X2 \end{bmatrix} = \hat{S}_0 \begin{bmatrix} \Delta P \\ \Delta Q \\ \Delta X2 \end{bmatrix} \qquad \text{--- (4.16)}$$

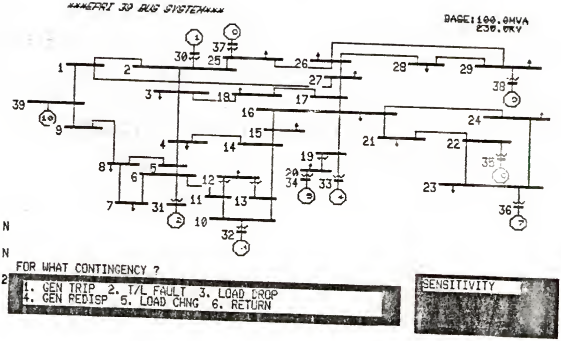
where $\hat{S}_{2p}$, $\hat{S}_{2q}$, $\hat{S}_{1q}$ and S_{12} are the matrices obtained similarly as S_{2p}, S_{2q} and S_{12} using the modified submatrices, $\hat{H}^{-1}$, $\hat{L}^{-1}$, $\hat{K}$ and $\hat{J}$.

4.3.2 Generator drop

In case of a generator drop, the type of the appropriate bus must be changed from a generator bus (P-V bus) into a load bus (P-Q bus). In addition, if the bus experiencing the generator drop is a slack bus, then another generator bus should be assigned as a slack bus instead. Since the total number of load buses are increased, submatrices K and L^{-1} and should be modified accordingly. One column in K, which was zero previously, must be computed using the prefault states and Eq. (4.14). Also, appropriate column in L^{-1}, which was composed of all zeros except only a one on the diagonal, should be computed using the Eq. (4.15). As a result of a generator drop, if a generator bus changes into a load bus, then the transformation matrix T is identical to an identity matrix except one column.

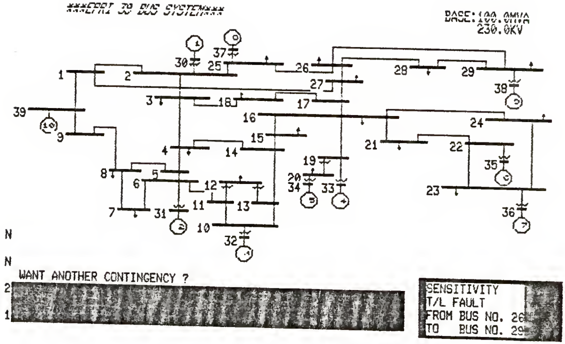
4.4 Numerical Results

A computer program implementing the proposed methods has been developed and applied to the 11 Bus System and the New England 39 Bus System as shown in Figs.(3.2) and (3.3). The Harris 800 with DEC GIGI terminal and BARCO color monitor was used to draw the system and to apply the contingencies interactively as shown in Figs.(4.1)and (4.2). Flow chart of the program is shown in Fig.(3.1). Sensitivity results can be compared with the exact solution



FOR WHAT CONTINGENCY ?

Fig. 4.1 Menu Driven Contingency Selection



WANT ANOTHER CONTINGENCY ?

SENSITIVITY
T/L FAULT
FROM BUS NO. 26
TO BUS NO. 29

Fig. 4.2 Transmission Line Fault (T/L 26-29 Trip and Blinking)

obtined using the full NR power flow method to check the accuracy of the solution. The sensitivity results together with voltage and power flow deviations from their accurate values can be displayed in either graphical or tabular form as shown in Figs.(4.3)-(4.4) and Tables (4.2)-(4.12) attached to the end of this chapter. To check the overall accuracy of each sensitivity method, the maximum and average deviations can also be computed. Refer to Table (4.13).

Base case operating conditions are arbitrarily assumed to create a relatively heavy loaded situation. The following assumptions were made to better evaluate the differences between each of the sensitivity methods:

i. Real power generations and generator bus voltages are fixed at their scheduled values.
ii. Loads are fixed at their scheduled values.
iii. Load bus voltages are not controlled.
iv. All taps of the load tap changers(LTCs) are fixed.
v. System is not separated as a result of any transmission line fault.

A number of single and multiple contingencies were simulated on the test system using all the sensitivity methods previously descrived. Some of the sensitivity results tested with the New England 39 Bus System are shown in Tables (4.2)-(4.10). The estimated states were compared with the accurate values obtained by the full NR method and their maximum and average deviations summarized in Table (4.13).

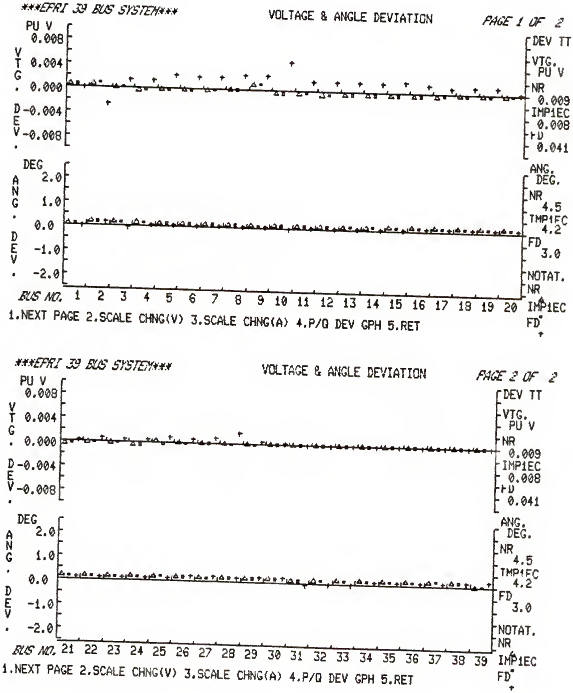


Fig. 4.3 Voltage and Angle Deviation from the Accurate Values (NR, EC and FD MethodS)

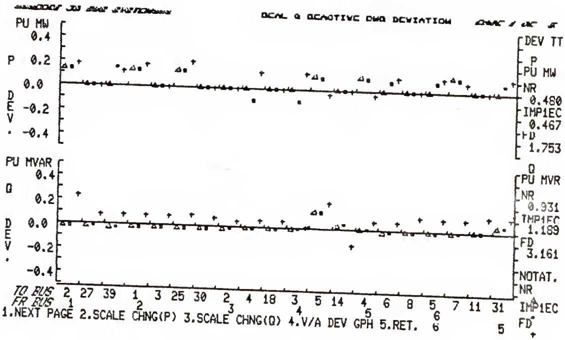


Fig. 4.4 Real and Reactive Power Deviation from the Accurate Values (NR, EC and FD Methods)

In most cases, the NR method together with the Decoupled NR method gives the most accurate results and the FD method the poorest. Even though the errors in the voltage magnitudes and the angles are relatively small in all of the methods, the real and reactive power flows on the lines are very sensitive even to the small relative deviations of the voltage magnitudes and angles between both end buses.

The errors of the FD method seem to become larger when the R/X ratio of the lines around the outaged elements are large. This is mainly because of the large admittance angle and the consequent growing of the significance of the off-diagonal submatrices in the Jacobian.

After the sensitivity analysis, power mismatches at each bus computed using the sensitivity results can be used as good indices for the accuracy of the sensitivity results. They are not necessary but sufficient conditions.

In general, the accuracies of the reactive power-flows are poor compared with the real power flows because of the nonlinearity of the cosine function in the small angle range. Since the errors are almost consistent both in magnitude and direction, properly chosen correction factors based on the prefault state and the system parameters could be used to reduce the deviations. One iteration of the reactive power estimates by updating the matrices L and J could be done if more accurate information on the reactive power flow is required.

Table 4.2 Sensitivity Results for the 39 Bus System
(T/L 1-2 Trip, Full NR Method)

```
* Sensitivity Analysis Method :  Full NR Method


*--  BUS DATA ---*   *GENERATION*  *---LOAD---*  *REAC*   *---  LINE FLOW  ---*
BS TY  VOLTS ANGLE     MW   MVAR     MW   MVAR    MVAR    TO LN     MW     MVAR
 1 L 1.09490  -1.28    1.4  -1.1     0.0   0.0     0.0    --------------------
                                                           2  1     0.0     0.0
                                                          27  2    77.4     7.9
                                                          39  3   -75.9    -9.0
 2 L 1.02425  -9.17    3.5   8.3     0.0   0.0     0.0    --------------------
                                                           1  1     0.0     0.0
                                                           3  4   193.1    96.6
                                                          25  5    90.4    39.5
                                                          30  6  -280.0-127.8
 6 L 1.00256  -5.23    0.0   0.7     0.0   0.0     0.0    --------------------
                                                           5 11   344.4 -23.0
                                                           7 13   125.5 -21.5
                                                          11 14   -33.9  63.6
                                                          31 15  -436.0 -18.4
10 L 0.99507  -4.80    0.0  -0.3     0.0   0.0     0.0    --------------------
                                                          11 19    90.3 -57.0
                                                          13 20   349.6 -28.2
                                                          32 21  -440.0  84.9
11 L 0.99703  -5.04    0.0  -0.1     0.0   0.0     0.0    --------------------
                                                           6 14    33.9 -77.0
                                                          10 19   -90.3  50.2
                                                          12 22    56.3  26.7
15 L 0.99449 -10.55    0.0  -0.1   176.0  42.4     0.0    --------------------
                                                          14 25  -237.3  -1.8
                                                          16 26    61.3 -40.7
16 L 0.99700 -10.90    0.0  -0.1   263.2 105.6     0.0    --------------------
                                                          15 26   -61.3  24.2
                                                          17 27   179.1 -46.8
                                                          19 28  -360.7  44.7
                                                          21 29   -79.7 -52.6
                                                          24 30    59.4 -75.2
20 L 0.98897  -7.26    0.0  -0.1   464.0 122.4     0.0    --------------------
                                                          19 33   -61.4 -30.3
                                                          34 35  -402.6 -92.2
24 L 1.00108 -11.12    0.0   0.1   247.2   8.0     0.0    --------------------
                                                          16 30   -59.3  68.9
                                                          23 39  -187.9 -76.8
25 L 1.01412  -9.42    0.7   1.7   179.2 117.6     0.0    --------------------
                                                           2  5   -89.7 -53.8
                                                          26 41   262.5 -11.0
                                                          37 47  -351.3 -51.1
31 V 1.01300   0.93  436.0  65.8     0.0   0.0     0.0    --------------------
                                                           6 15   436.0  65.8
39 S 1.05400   0.53  186.7-278.7     0.0   0.0     0.0    --------------------
                                                           1  3    76.5-220.0
                                                           9 18   110.2 -58.7
```

Table 4.3 Sensitivity Results for the 39 Bus System
(T/L 1-2 Trip, Decoupled NR Method)

```
* Sensitivity Analysis Method :  Decoupled NR Method


*--  BUS DATA ---*  *GENERATION*  *---LOAD---*  *REAC*     *---  LINE FLOW   ---*
BS TY  VOLTS  ANGLE    MW  MVAR     MW   MVAR    MVAR      TO LN      MW      MVAR
 1 L 1.09490  -1.28   1.4  -1.1     0.0   0.0     0.0
                                                           ----------------------
                                                            2  1      0.0     0.0
                                                           27  2     77.4     7.9
 2 L 1.02425  -9.17   3.5   8.3     0.0   0.0     0.0      39  3    -75.9    -9.0
                                                           ----------------------
                                                            1  1      0.0     0.0
                                                            3  4    193.1    96.6
                                                           25  5     90.4    39.5
 6 L 1.00256  -5.23   0.0   0.7     0.0   0.0     0.0      30  6   -280.0-127.8
                                                           ----------------------
                                                            5 11    344.4   -23.0
                                                            7 13    125.5   -21.5
                                                           11 14    -33.9    63.6
10 L 0.99507  -4.80   0.0  -0.3     0.0   0.0     0.0      31 15   -436.0   -18.4
                                                           ----------------------
                                                           11 19     90.3   -57.0
                                                           13 20    349.6   -28.2
11 L 0.99703  -5.04   0.0  -0.1     0.0   0.0     0.0      32 21   -440.0    84.9
                                                           ----------------------
                                                            6 14     33.9   -77.0
                                                           10 19    -90.3    50.2
15 L 0.99449 -10.55   0.0  -0.1   176.0  42.4     0.0      12 22     56.3    26.7
                                                           ----------------------
                                                           14 25   -237.3    -1.8
16 L 0.99700 -10.90   0.0  -0.1   263.2 105.6     0.0      16 26     61.3   -40.7
                                                           ----------------------
                                                           15 26    -61.3    24.2
                                                           17 27    179.1   -46.8
                                                           19 28   -360.7    44.7
                                                           21 29    -79.7   -52.6
20 L 0.98897  -7.26   0.0  -0.1   464.0 122.4     0.0      24 30     59.4   -75.2
                                                           ----------------------
                                                           19 33    -61.4   -30.3
24 L 1.00108 -11.12   0.0   0.1   247.2   8.0     0.0      34 35   -402.6   -92.2
                                                           ----------------------
                                                           16 30    -59.3    68.9
25 L 1.01412  -9.42   0.7   1.7   179.2 117.6     0.0      23 39   -187.9   -76.8
                                                           ----------------------
                                                            2  5    -89.7   -53.8
                                                           26 41    262.5   -11.0
31 V 1.01300   0.93 436.0  65.8     0.0   0.0     0.0      37 47   -351.3   -51.1
                                                           ----------------------
39 S 1.05400   0.53 186.7-278.7     0.0   0.0     0.0       6 15    436.0    65.8
                                                           ----------------------
                                                            1  3     76.5-220.0
                                                            9 18    110.2   -58.7
```

Table 4.4 Sensitivity Results for the 39 Bus System
(T/L 1-2 Trip, Accelerated NR Method)

```
* Sensitivity Analysis Method :  Accelerated NR Method


*--  BUS DATA ---*  *GENERATION*  *---LOAD---*  *REAC*     *---  LINE FLOW   ---*
BS TY  VOLTS ANGLE     MW  MVAR     MW   MVAR    MVAR      TO LN         MW   MVAR

 1 L 1.09490  -1.28    1.4  -1.1    0.0    0.0    0.0   -----------------------
                                                        2  1         0.0   0.0
                                                       27  2        77.4   7.9
                                                       39  3       -75.9  -9.0
 2 L 1.02425  -9.17    3.5   8.3    0.0    0.0    0.0   -----------------------
                                                        1  1         0.0   0.0
                                                        3  4       193.1  96.6
                                                       25  5        90.4  39.5
                                                       30  6      -280.0-127.8
 6 L 1.00256  -5.23    0.0   0.7    0.0    0.0    0.0   -----------------------
                                                        5 11       344.4 -23.0
                                                        7 13       125.5 -21.5
                                                       11 14       -33.9  63.6
                                                       31 15      -436.0 -18.4
10 L 0.99507  -4.80    0.0  -0.3    0.0    0.0    0.0   -----------------------
                                                       11 19        90.3 -57.0
                                                       13 20       349.6 -28.2
                                                       32 21      -440.0  84.9
11 L 0.99703  -5.04    0.0  -0.1    0.0    0.0    0.0   -----------------------
                                                        6 14        33.9 -77.0
                                                       10 19       -90.3  50.2
                                                       12 22        56.3  26.7
15 L 0.99449 -10.55    0.0  -0.1  176.0   42.4    0.0   -----------------------
                                                       14 25      -237.3  -1.8
                                                       16 26        61.3 -40.7
16 L 0.99700 -10.90    0.0  -0.1  263.2  105.6    0.0   -----------------------
                                                       15 26       -61.3  24.2
                                                       17 27       179.1 -46.8
                                                       19 28      -360.7  44.7
                                                       21 29       -79.7 -52.6
                                                       24 30        59.4 -75.2
20 L 0.98897  -7.26    0.0  -0.1  464.0  122.4    0.0   -----------------------
                                                       19 33       -61.4 -30.3
                                                       34 35      -402.6 -92.2
24 L 1.00108 -11.12    0.0   0.1  247.2    8.0    0.0   -----------------------
                                                       16 30       -59.3  68.9
                                                       23 39      -187.9 -76.8
25 L 1.01412  -9.42    0.7   1.7  179.2  117.6    0.0   -----------------------
                                                        2  5       -89.7 -53.8
                                                       26 41       262.5 -11.0
                                                       37 47      -351.3 -51.1
31 V 1.01300   0.93  436.0  65.8    0.0    0.0    0.0   -----------------------
                                                        6 15       436.0  65.8
39 S 1.05400   0.53  186.7-278.7    0.0    0.0    0.0   -----------------------
                                                        1  3        76.5-220.0
                                                        9 18       110.2 -58.7
```

Table 4.5 Sensitivity Results for the 39 Bus System
(T/L 1-2 Trip, Imp. Version 1 EC Method)

```
* Sensitivity Analysis Method :  Imp. Version 1 EC method


*--  BUS DATA ---*   *GENERATION*  *---LOAD---*  *REAC*    *---  LINE FLOW   ---*
BS TY  VOLTS ANGLE      MW  MVAR      MW   MVAR    MVAR     TO LN       MW    MVAR
                                                           ---------------------
 1 L 1.09489  -1.28    1.4  -1.1     0.0    0.0     0.0     2  1      0.0     0.0
                                                           27  2     77.3     7.9
                                                           39  3    -75.9    -9.0
 2 L 1.02453  -9.18    3.4  19.3     0.0    0.0     0.0    ---------------------
                                                            1  1      0.0     0.0
                                                            3  4    192.6    97.7
                                                           25  5     90.8    47.8
                                                           30  6   -280.0-126.2
 6 L 1.00259  -5.23    0.0   0.6     0.0    0.0     0.0    ---------------------
                                                            5 11    344.5   -23.2
                                                            7 13    125.5   -21.6
                                                           11 14    -33.9    63.7
                                                           31 15   -436.0   -18.3
10 L 0.99510  -4.81    0.0  -0.3     0.0    0.0     0.0    ---------------------
                                                           11 19     90.3   -57.0
                                                           13 20    349.6   -28.3
                                                           32 21   -440.0    85.0
11 L 0.99705  -5.05    0.0  -0.1     0.0    0.0     0.0    ---------------------
                                                            6 14     34.0   -77.1
                                                           10 19    -90.3    50.3
                                                           12 22     56.3    26.7
15 L 0.99451 -10.56    0.0  -0.1   176.0   42.4     0.0    ---------------------
                                                           14 25   -237.2    -1.9
                                                           16 26     61.2   -40.6
16 L 0.99701 -10.91    0.0  -0.1   263.2  105.6     0.0    ---------------------
                                                           15 26    -61.2    24.1
                                                           17 27    179.0   -46.8
                                                           19 28   -360.8    44.8
                                                           21 29    -79.7   -52.6
                                                           24 30     59.4   -75.1
20 L 0.98897  -7.26    0.0  -0.1   464.0  122.4     0.0    ---------------------
                                                           19 33    -61.4   -30.3
                                                           34 35   -402.6   -92.1
25 L 1.01368  -9.40    0.8  -9.4   179.2  117.6     0.0    ---------------------
                                                            2  5    -90.0   -62.0
                                                           26 41    262.9   -12.0
                                                           37 47   -351.3   -53.0
31 V 1.01300   0.93  436.0  65.6     0.0    0.0     0.0    ---------------------
                                                            6 15    436.0    65.6
39 S 1.05400   0.53  186.8-278.7     0.0    0.0     0.0    ---------------------
                                                            1  3     76.5-220.0
                                                            9 18    110.3   -58.7
```

Table 4.6 Sensitivity Results for the 39 Bus System
(T/L 1-2 Trip, Imp. Version 2 EC Method)

```
* Sensitivity Analysis Method :  Imp. Version 2 EC Method


*--  BUS DATA ---*  *GENERATION*  *---LOAD---*  *REAC*    *---  LINE FLOW   ---*
BS TY  VOLTS ANGLE     MW   MVAR     MW    MVAR   MVAR     TO LN      MW      MVAR

 1 L 1.09503  -1.28    1.4  -0.8    0.0    0.0    0.0    ---------------------
                                                           2  1      0.0    0.0
                                                          27  2     77.4    7.8
 2 L 1.02356  -9.13    3.8 -20.2    0.0    0.0    0.0     39  3    -75.9   -8.6
                                                         ---------------------
                                                           1  1      0.0    0.0
                                                           3  4    194.4   93.5
                                                          25  5     89.3   17.9
 6 L 1.00249  -5.21    0.0   0.7    0.0    0.0    0.0     30  6   -280.0-131.6
                                                         ---------------------
                                                           5 11    344.3  -22.6
                                                           7 13    125.6  -21.5
                                                          11 14    -33.9   63.5
10 L 0.99502  -4.79    0.0  -0.3    0.0    0.0    0.0     31 15   -436.0  -18.7
                                                         ---------------------
                                                          11 19     90.4  -56.8
                                                          13 20    349.6  -28.1
11 L 0.99697  -5.02    0.0   0.0    0.0    0.0    0.0     32 21   -440.0   84.6
                                                         ---------------------
                                                           6 14     34.0  -76.8
                                                          10 19    -90.3   50.1
15 L 0.99450 -10.54    0.0   0.1  176.0   42.4    0.0     12 22     56.3   26.7
                                                         ---------------------
                                                          14 25   -237.5   -1.4
16 L 0.99703 -10.89    0.0   0.0  263.2  105.6    0.0     16 26     61.5  -41.0
                                                         ---------------------
                                                          15 26    -61.5   24.5
                                                          17 27    179.3  -47.1
                                                          19 28   -360.7   44.8
                                                          21 29    -79.7  -52.6
20 L 0.98898  -7.24    0.0   0.0  464.0  122.4    0.0     24 30     59.4  -75.2
                                                         ---------------------
                                                          19 33    -61.4  -30.3
24 L 1.00111 -11.10    0.0   0.2  247.2    8.0    0.0     34 35   -402.6  -92.1
                                                         ---------------------
                                                          16 30    -59.3   68.9
25 L 1.01532  -9.45    0.6  30.4  179.2  117.6    0.0     23 39   -187.9  -76.7
                                                         ---------------------
                                                           2  5    -88.8  -32.4
                                                          26 41    261.4   -8.9
31 V 1.01300   0.95  436.0  66.1    0.0    0.0    0.0     37 47   -351.3  -45.9
                                                         ---------------------
39 S 1.05400   0.53  186.4-278.8    0.0    0.0    0.0      6 15    436.0   66.1
                                                         ---------------------
                                                           1  3     76.5-220.4
                                                           9 18    109.9  -58.4
```

Table 4.7 Sensitivity Results for the 39 Bus System
(T/L 1-2 Trip, Epsilon Coupling Method)

```
* Sensitivity Analysis Method :  Epsilon Coupling Method


*--  BUS DATA ---*      *GENERATION*   *---LOAD---*  *REAC*     *---  LINE FLOW   ---*
BS TY  VOLTS ANGLE        MW  MVAR       MW    MVAR   MVAR       TO LN     MW      MVAR

  1 L 1.09503  -1.27     1.9  -0.8     0.0    0.0    0.0       ---------------------
                                                                2  1      0.0     0.0
                                                               27  2     77.5     7.8
  2 L 1.02356  -9.19    -9.0 -11.3     0.0    0.0    0.0       39  3    -75.6    -8.7
                                                               ---------------------
                                                                1  1      0.0     0.0
                                                                3  4    192.3    93.6
                                                               25  5     78.4    26.7
  6 L 1.00249  -5.25    -0.1   0.7     0.0    0.0    0.0       30  6   -279.7-131.6
                                                               ---------------------
                                                                5 11    344.2 -22.6
                                                                7 13    125.3 -21.4
                                                               11 14    -33.9  63.5
 10 L 0.99502  -4.82    -0.1  -0.3     0.0    0.0    0.0       31 15   -435.7 -18.7
                                                               ---------------------
                                                               11 19     90.2 -56.8
                                                               13 20    349.4 -28.1
 11 L 0.99697  -5.06     0.0   0.0     0.0    0.0    0.0       32 21   -439.7  84.6
                                                               ---------------------
                                                                6 14     33.9 -76.8
                                                               10 19    -90.2  50.1
 15 L 0.99450 -10.57     0.2   0.0   176.0   42.4    0.0       12 22     56.3  26.7
                                                               ---------------------
                                                               14 25   -237.0  -1.4
 16 L 0.99703 -10.92     0.1   0.0   263.2  105.6    0.0       16 26     61.2 -40.9
                                                               ---------------------
                                                               15 26    -61.1  24.4
                                                               17 27    179.0 -47.1
                                                               19 28   -360.6  44.8
                                                               21 29    -79.7 -52.6
 20 L 0.98898  -7.27     0.0   0.0   464.0  122.4    0.0       24 30     59.3 -75.2
                                                               ---------------------
                                                               19 33    -61.4 -30.3
 24 L 1.00111 -11.13     0.1   0.1   247.2    8.0    0.0       34 35   -402.6 -92.1
                                                               ---------------------
                                                               16 30    -59.3  68.9
 25 L 1.01532  -9.43    12.9  21.4   179.2  117.6    0.0       23 39   -187.8 -76.7
                                                               ---------------------
                                                                2  5    -77.9 -41.3
                                                               26 41    263.0  -8.9
 31 V 1.01300   0.91   435.7  66.0     0.0    0.0    0.0       37 47   -351.5 -45.9
                                                               ---------------------
 39 S 1.05400   0.53   186.8-278.8     0.0    0.0    0.0        6 15    435.7  66.0
                                                               ---------------------
                                                                1  3     76.1-220.4
                                                                9 18    110.7 -58.5
```

Table 4.8 Sensitivity Results for the 39 Bus System
(T/L 1-2 Trip, Imp.FD Method)

```
* Sensitivity Analysis Method :  Imp. FD Method


*--  BUS DATA ---*   *GENERATION*  *---LOAD---*  *REAC*     *---  LINE FLOW   ---*
BS TY  VOLTS ANGLE      MW   MVAR      MW   MVAR   MVAR     TO LN     MW      MVAR

 1 L 1.09236  -1.27    1.3  -8.3     0.0    0.0    0.0
                                                           ---------------------
                                                            2  1        0.0    0.0
                                                           27  2       77.2    6.9
 2 L 1.02464  -9.19    3.2  11.9     0.0    0.0    0.0     39  3      -76.0  -15.2
                                                           ---------------------
                                                            1  1        0.0    0.0
                                                            3  4      192.9   96.2
                                                           25  5       90.3   41.3
 6 L 1.00327  -5.25    0.0  -0.3     0.0    0.0    0.0     30  6     -280.0-125.6
                                                           ---------------------
                                                            5 11      344.5  -26.2
                                                            7 13      125.4  -23.0
                                                           11 14      -33.8   64.5
10 L 0.99568  -4.82    0.0   0.0     0.0    0.0    0.0     31 15     -436.0  -15.6
                                                           ---------------------
                                                           11 19       90.3  -57.8
                                                           13 20      349.7  -30.1
11 L 0.99767  -5.06    0.0  -0.2     0.0    0.0    0.0     32 21     -440.0   87.9
                                                           ---------------------
                                                            6 14       33.9  -77.9
                                                           10 19      -90.2   51.1
15 L 0.99506 -10.57    0.0   0.6   176.0   42.4    0.0     12 22       56.4   26.6
                                                           ---------------------
                                                           14 25     -237.4   -2.8
16 L 0.99741 -10.92    0.0   0.5   263.2  105.6    0.0     16 26       61.4  -39.0
                                                           ---------------------
                                                           15 26      -61.4   22.4
                                                           17 27      179.2  -47.3
                                                           19 28     -360.7   46.1
                                                           21 29      -79.7  -51.7
20 L 0.98905  -7.27    0.0   0.0   464.0  122.4    0.0     24 30       59.4  -74.6
                                                           ---------------------
                                                           19 33      -61.4  -30.7
24 L 1.00145 -11.13    0.0   0.1   247.2    8.0    0.0     34 35     -402.6  -91.7
                                                           ---------------------
                                                           16 30      -59.3   68.3
25 L 1.01437  -9.43    0.8   0.9   179.2  117.6    0.0     23 39     -187.9  -76.2
                                                           ---------------------
                                                            2  5      -89.6  -55.6
                                                           26 41      262.5  -11.0
31 V 1.01300   0.91  436.0  62.9     0.0    0.0    0.0     37 47     -351.3  -50.0
                                                           ---------------------
39 S 1.05400   0.53  187.0-275.0     0.0    0.0    0.0      6 15      436.0   62.9
                                                           ---------------------
                                                            1  3       76.5-213.8
                                                            9 18      110.6  -61.3
```

Table 4.9 Sensitivity Results for the 39 Bus System
(T/L 1-2 Trip, FD Method)

```
* Sensitivity Analysis Method :  FD Method


*--- BUS DATA ---*    *GENERATION*   *---LOAD---*  *REAC*      *---  LINE FLOW   ---*
BS TY  VOLTS ANGLE       MW   MVAR     MW    MVAR    MVAR       TO LN      MW      MVAR

 1 L 1.09236   -1.23    4.8   -8.3    0.0    0.0     0.0     --------------------
                                                              2  1         0.0    0.0
                                                             27  2        78.7    7.1
 2 L 1.02464   -9.58  -30.2   32.2    0.0    0.0     0.0     39  3       -73.9  -15.4
                                                             --------------------
                                                              1  1         0.0    0.0
                                                              3  4       181.1   96.9
                                                             25  5        66.0   61.0
 6 L 1.00327   -5.49   -0.2   -0.4    0.0    0.0     0.0     30  6      -277.3-125.8
                                                             --------------------
                                                              5 11       344.7  -26.2
                                                              7 13       123.4  -22.9
                                                             11 14       -32.9   64.4
10 L 0.99568   -5.07   -0.1    0.0    0.0    0.0     0.0     31 15      -435.4  -15.7
                                                             --------------------
                                                             11 19        89.4  -57.7
                                                             13 20       350.0  -30.2
11 L 0.99767   -5.30    0.0   -0.2    0.0    0.0     0.0     32 21      -439.5   87.9
                                                             --------------------
                                                              6 14        33.0  -77.8
                                                             10 19       -89.3   51.0
15 L 0.99506 -10.80     0.6    0.5  176.0   42.4     0.0     12 22        56.3   26.6
                                                             --------------------
                                                             14 25      -236.5   -2.9
16 L 0.99741 -11.15     0.4    0.5  263.2  105.6     0.0     16 26        61.2  -38.9
                                                             --------------------
                                                             15 26       -61.1   22.4
                                                             17 27       179.3  -47.3
                                                             19 28      -360.4   46.0
                                                             21 29       -79.7  -51.7
20 L 0.98905   -7.51    0.2    0.0  464.0  122.4     0.0     24 30        59.0  -74.6
                                                             --------------------
                                                             19 33       -61.3  -30.7
24 L 1.00145 -11.36     0.5    0.1  247.2    8.0     0.0     34 35      -402.6  -91.7
                                                             --------------------
                                                             16 30       -59.0   68.3
25 L 1.01437   -9.62   25.5  -19.0  179.2  117.6     0.0     23 39      -187.6  -76.2
                                                             --------------------
                                                              2  5       -65.4  -75.5
                                                             26 41       261.7  -11.0
31 V 1.01300    0.66  435.4   62.8    0.0    0.0     0.0     37 47      -350.1  -50.2
                                                             --------------------
39 S 1.05400    0.53  188.8-275.0     0.0    0.0     0.0      6 15       435.4   62.8
                                                             --------------------
                                                              1  3        74.4-213.7
                                                              9 18       114.4  -61.4
```

Table 4.10 Full Power Flow Solution for the 39 Bus System
(T/L 1-2 Trip, Full NR Method)

* Power Flow Method : Full NR Method

* No. of Iterations : 6

-- BUS DATA ---				*GENERATION*		*---LOAD---*		*REAC*	*--- LINE FLOW ---*			
BS	TY	VOLTS	ANGLE	MW	MVAR	MW	MVAR	MVAR	TO	LN	MW	MVAR
1	L	1.09502	-1.33	0.0	0.0	0.0	0.0	0.0	2	1	0.0	0.0
									27	2	78.4	8.4
									39	3	-78.4	-8.4
2	L	1.02318	-9.42	0.0	0.0	0.0	0.0	0.0	1	1	0.0	0.0
									3	4	190.3	96.4
									25	5	89.7	37.3
									30	6	-280.0	-133.7
6	L	1.00186	-5.41	0.0	0.0	0.0	0.0	0.0	5	11	344.7	-20.6
									7	13	124.4	-19.9
									11	14	-33.1	61.7
									31	15	-436.0	-21.2
10	L	0.99460	-5.00	0.0	0.0	0.0	0.0	0.0	11	19	89.6	-55.2
									13	20	350.4	-27.3
									32	21	-440.0	82.5
11	L	0.99648	-5.23	0.0	0.0	0.0	0.0	0.0	6	14	33.1	-75.1
									10	19	-89.5	48.4
									12	22	56.4	26.6
15	L	0.99394	-10.77	0.0	0.0	176.0	42.4	0.0	14	25	-238.1	-1.2
									16	26	62.1	-41.2
16	L	0.99650	-11.13	0.0	0.0	263.2	105.6	0.0	15	26	-62.1	24.7
									17	27	179.9	-44.1
									19	28	-360.7	43.0
									21	29	-79.6	-53.5
									24	30	59.4	-75.6
20	L	0.98888	-7.48	0.0	0.0	464.0	122.4	0.0	19	33	-61.4	-29.8
									34	35	-402.6	-92.6
24	L	1.00060	-11.34	0.0	0.0	247.2	8.0	0.0	16	30	-59.4	69.4
									23	39	-187.8	-77.4
25	L	1.01327	-9.67	0.0	0.0	179.2	117.6	0.0	2	5	-89.1	-51.7
									26	41	261.1	-11.2
									37	47	-351.3	-54.8
31	V	1.01300	0.75	436.0	68.6	0.0	0.0	0.0	6	15	436.0	68.6
39	S	1.05400	0.53	192.1	-277.5	0.0	0.0	0.0	1	3	79.0	-220.5
									9	18	113.1	-57.0

Table 4.11 Deviation of the Sensitivity Results from the Accurate Values for the 39 Bus System (T/L 1-2 Trip, Full NR)

* Sensitivity Analysis Method : Full NR Method

BUS NO,	VOLT DEV (PU V)	ANG DEV (DEG)	**** TL PWR FLOW DEV ****		
			TO BUS	P DEV	Q DEV
1	0.000	0.1	2	0.00	0.00
			27	0.01	0.00
			39	-0.02	0.00
2	0.001	0.3	1	0.00	0.00
			3	-0.03	0.00
			25	-0.01	-0.02
			30	0.00	-0.06
6	0.001	0.2	5	0.00	-0.02
			7	-0.01	0.02
			11	0.01	-0.02
			31	0.00	-0.03
10	0.000	0.2	11	-0.01	0.02
			13	0.01	0.01
			32	0.00	-0.02
11	0.001	0.2	6	0.01	-0.02
			10	-0.01	0.02
			12	0.00	0.00
15	0.001	0.2	14	0.01	-0.01
			16	0.01	0.00
16	0.001	0.2	15	0.01	0.00
			17	0.01	0.03
			19	0.00	-0.02
			21	0.00	-0.01
			24	0.00	0.00
20	0.000	0.2	19	0.00	-0.01
			34	0.00	-0.01
24	0.000	0.2	16	0.00	0.00
			23	0.00	0.01
25	0.001	0.3	2	-0.01	-0.02
			26	-0.01	0.00
			37	0.00	-0.04
31	0.000	0.2	6	0.00	-0.03
39	0.000	0.0	1	-0.02	0.00
			9	-0.03	-0.02

Table 4.12 Deviation of the Sensitivity Results from the Accurate Values for the 39 Bus System (T/L 1-2 Trip, Imp. V-1 EC)

* Sensitivity Analysis Method : Imp. Version 1 EC Method

BUS NO,	VOLT DEV (PU V)	ANG DEV (DEG)	**** TL PWR FLOW DEV ****		
			TO BUS	P DEV	Q DEV
1	0.000	0.1	2	0.00	0.00
			27	0.01	0.00
			39	-0.02	0.00
2	0.001	0.2	1	0.00	0.00
			3	-0.02	-0.01
			25	-0.01	-0.10
			30	0.00	-0.08
6	0.001	0.2	5	0.00	-0.03
			7	-0.01	0.02
			11	0.01	-0.02
			31	0.00	-0.03
10	0.001	0.2	11	-0.01	0.02
			13	0.01	0.01
			32	0.00	-0.02
11	0.001	0.2	6	0.01	-0.02
			10	-0.01	0.02
			12	0.00	0.00
15	0.001	0.2	14	0.01	-0.01
			16	0.01	-0.01
16	0.001	0.2	15	0.01	-0.01
			17	0.01	0.03
			19	0.00	-0.02
			21	0.00	-0.01
			24	0.00	-0.01
20	0.000	0.2	19	0.00	-0.01
			34	0.00	-0.01
24	0.000	0.2	16	0.00	-0.01
			23	0.00	0.01
25	0.000	0.3	2	-0.01	-0.10
			26	-0.02	0.01
			37	0.00	-0.02
31	0.000	0.2	6	0.00	-0.03
39	0.000	0.0	1	-0.02	0.00
			9	-0.03	-0.02

Table 4.13 Max. and Avg. Deviation of the Sensitivity Results for the 39 Bus System with T/L No. 1 Trip (all methods)

* Full NR Method

```
***** MAX DEVIATION INFORMATION *****

 MAX VTG DEVIATION       :   BUS NO. ; 9     DEV    ; 0.00125
 MAX ANG DEVIATION       :   BUS NO. ;25     DEV    ;  0.258
 MAX P DEV   :    FROM BUS  ; 39    TO BUS ;      9     DEV   ;   0.0296
 MAX Q DEV   :    FROM BUS  ; 30    TO BUS ;      2     DEV   ;   0.0622
***** TOTAL DEVIATION INFORMATION *****

 TOTAL VOLTAGE DEV   (PU V) :        0.018
 TOTAL ANGLE DEV (DEG)      :          8.0
 TOTAL P DEV (PU MW)        :        0.614
 TOTAL Q DEV (PU MVAR)      :        1.154
```

* DC NR Method

```
***** MAX DEVIATION INFORMATION *****

 MAX VTG DEVIATION       :   BUS NO. ; 9     DEV    ; 0.00125
 MAX ANG DEVIATION       :   BUS NO. ;25     DEV    ;  0.258
 MAX P DEV   :    FROM BUS  ; 39    TO BUS ;      9     DEV   ;   0.0296
 MAX Q DEV   :    FROM BUS  ; 30    TO BUS ;      2     DEV   ;   0.0622
***** TOTAL DEVIATION INFORMATION *****

 TOTAL VOLTAGE DEV   (PU V) :        0.018
 TOTAL ANGLE DEV (DEG)      :          8.0
 TOTAL P DEV (PU MW)        :        0.614
 TOTAL Q DEV (PU MVAR)      :        1.154
```

* Acc. NR Method

```
***** MAX DEVIATION INFORMATION *****

 MAX VTG DEVIATION       :   BUS NO. ; 9     DEV    ; 0.00125
 MAX ANG DEVIATION       :   BUS NO. ;25     DEV    ;  0.258
 MAX P DEV   :    FROM BUS  ; 39    TO BUS ;      9     DEV   ;   0.0296
 MAX Q DEV   :    FROM BUS  ; 30    TO BUS ;      2     DEV   ;   0.0622
***** TOTAL DEVIATION INFORMATION *****

 TOTAL VOLTAGE DEV   (PU V) :        0.018
 TOTAL ANGLE DEV (DEG)      :          8.0
 TOTAL P DEV (PU MW)        :        0.614
 TOTAL Q DEV (PU MVAR)      :        1.154
```

Table 4.13-continued

```
* Imp. Version 1 EC Method

***** MAX DEVIATION INFORMATION *****

 MAX VTG DEVIATION       :   BUS NO. ; 2     DEV    ; 0.00136
 MAX ANG DEVIATION       :   BUS NO. ;25     DEV    ;  0.272
 MAX P DEV   :    FROM BUS   ; 39    TO BUS ;     9     DEV   ;   0.0285
 MAX Q DEV   :    FROM BUS   ;  2    TO BUS ;    25     DEV   ;   0.1046

***** TOTAL DEVIATION INFORMATION *****

 TOTAL VOLTAGE DEV  (PU V) :         0.018
 TOTAL ANGLE DEV (DEG)     :           7.8
 TOTAL P DEV (PU MW)       :         0.610
 TOTAL Q DEV (PU MVAR)     :         1.396


* Imp. Version 2 EC Method

***** MAX DEVIATION INFORMATION *****

 MAX VTG DEVIATION       :   BUS NO. ;25     DEV    ; 0.00205
 MAX ANG DEVIATION       :   BUS NO. ; 2     DEV    ;  0.292
 MAX P DEV   :    FROM BUS   ;  2    TO BUS ;     3     DEV   ;   0.0417
 MAX Q DEV   :    FROM BUS   ;  2    TO BUS ;    25     DEV   ;   0.1945

***** TOTAL DEVIATION INFORMATION *****

 TOTAL VOLTAGE DEV  (PU V) :         0.018
 TOTAL ANGLE DEV (DEG)     :           8.4
 TOTAL P DEV (PU MW)       :         0.675
 TOTAL Q DEV (PU MVAR)     :         1.591


* EC Method

***** MAX DEVIATION INFORMATION *****

 MAX VTG DEVIATION       :   BUS NO. ;25     DEV    ; 0.00205
 MAX ANG DEVIATION       :   BUS NO. ;25     DEV    ;  0.249
 MAX P DEV   :    FROM BUS   ;  2    TO BUS ;    25     DEV   ;   0.1136
 MAX Q DEV   :    FROM BUS   ;  2    TO BUS ;    25     DEV   ;   0.1060

***** TOTAL DEVIATION INFORMATION *****

 TOTAL VOLTAGE DEV  (PU V) :         0.018
 TOTAL ANGLE DEV (DEG)     :           7.5
 TOTAL P DEV (PU MW)       :         0.882
 TOTAL Q DEV (PU MVAR)     :         1.402
```

Table 4.13-continued

* Imp. FD Method

```
***** MAX DEVIATION INFORMATION *****

 MAX VTG DEVIATION       :   BUS NO. ; 9      DEV   ; 0.00311
 MAX ANG DEVIATION       :   BUS NO. ;25      DEV   ;  0.249
 MAX P DEV   :   FROM BUS   ;  2    TO BUS ;    3     DEV   ;   0.0262
 MAX Q DEV   :   FROM BUS   ; 30    TO BUS ;    2     DEV   ;   0.0848
***** TOTAL DEVIATION INFORMATION *****

 TOTAL VOLTAGE DEV  (PU V) :          0.035
 TOTAL ANGLE DEV (DEG)     :            7.5
 TOTAL P DEV (PU MW)       :          0.565
 TOTAL Q DEV (PU MVAR)     :          2.197
```

* FD Method

```
***** MAX DEVIATION INFORMATION *****

 MAX VTG DEVIATION       :   BUS NO. ; 9      DEV   ; 0.00311
 MAX ANG DEVIATION       :   BUS NO. ;30      DEV   ;  0.184
 MAX P DEV   :   FROM BUS   ;  2    TO BUS ;   25     DEV   ;   0.2376
 MAX Q DEV   :   FROM BUS   ; 25    TO BUS ;    2     DEV   ;   0.2381
***** TOTAL DEVIATION INFORMATION *****

 TOTAL VOLTAGE DEV  (PU V) :          0.035
 TOTAL ANGLE DEV (DEG)     :            2.2
 TOTAL P DEV (PU MW)       :          1.449
 TOTAL Q DEV (PU MVAR)     :          2.623
```

CHAPTER 5
FURTHER RESEARCH AND CONCLUDING REMARKS

5.1 Application of Computer Graphics

The Digital Equipment Corporaton GIGI (the General Imaging Generator and Interpreter) graphics terminal which is connected to the Harris H-800 has been used in this work for overall power system analysis. GIGI provides local (in-terminal) processing using a micro processor which supports two interpreters: a ReGIS (the Remote Graphics Instruction Set) graphics interpreter and GIGI BASIC language interpreter. GIGI system configuration is shown in Fig(5.1). The image is maintained in display memory which is refreshed every 60th of a second. X coordinates range from 0 (the left edge of the screen) to 767 (the right edge of the screen). Y coordinates range from 0 (the top edge of the screen) to 479 (the bottom edge of the screen).

A computer program has been developed which can draw a power system one line diagram. System data can be displayed directly on the one line diagram and modified if necessary. Displays of system structural changes are also possible. Any type of contingencies can be reflected interactively by changes in the components color and by causing the component to blink.

Computer graphics was used to perform the power system analysis more effectively and efficiently. Some of the major features of the program are:

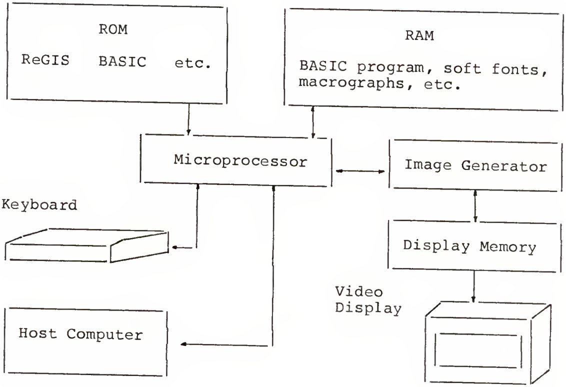


Fig. 5.1 GIGI Microprocessor and Terminal System

1). For convenience, any user defined coordinate can be used for bus locations. The program maps the user coordinates into the screen coordinates.

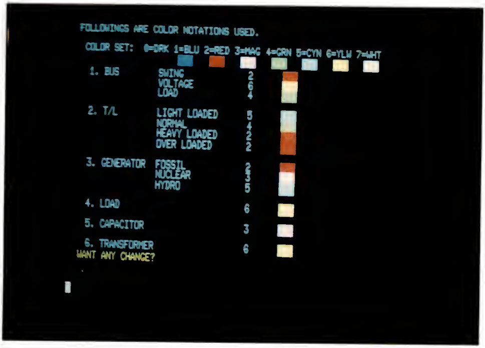
2). Instead of dealing with detailed coordinates to draw a one line diagram, several reference lines are used along with X and Y axis. And the bus coordinates can be expressed with the relative deviations from these reference lines instead of using the absolute coordinates.

3). Components with different functions and characteristics are distinguished by colors. For example,

Bus	Color
swing bus	red
vtg. control bus	yellow
load bus	green
T/L	
light loaded	yellow
normal loaded	green
heavy loaded	red
over loaded	red(blink)

The colors can be changed interactively. Refer to Fig. (5.2).

4). Each data location can be selected and adjusted interactively using the locator mode. In the locator mode, a cross-haired cursor appears on the screen. The cursor can be moved using the arrow keys, and the current screen coordinate of the cursor can be read in by typing ´R´. Once



```
FOLLOWINGS ARE COLOR NOTATIONS USED.
 COLOR SET:  0=DRK 1=BLU 2=RED 3=MAG 4=GRN 5=CYN 6=YLW 7=WHT
  1. BUS           SWING            2
                   VOLTAGE          6
                   LOAD             4
  2. T/L           LIGHT LOADED     5
                   NORMAL           4
                   HEAVY LOADED     2
                   OVER LOADED      2
  3. GENERATOR     FOSSIL           2
                   NUCLEAR          3
                   HYDRO            5
  4. LOAD                           6
  5. CAPACITOR                      3
  6. TRANSFORMER                    6
WANT ANY CHANGE?
```

Fig. 5.2 Interactive Color Selection for Power System Components in the One Line Diagram

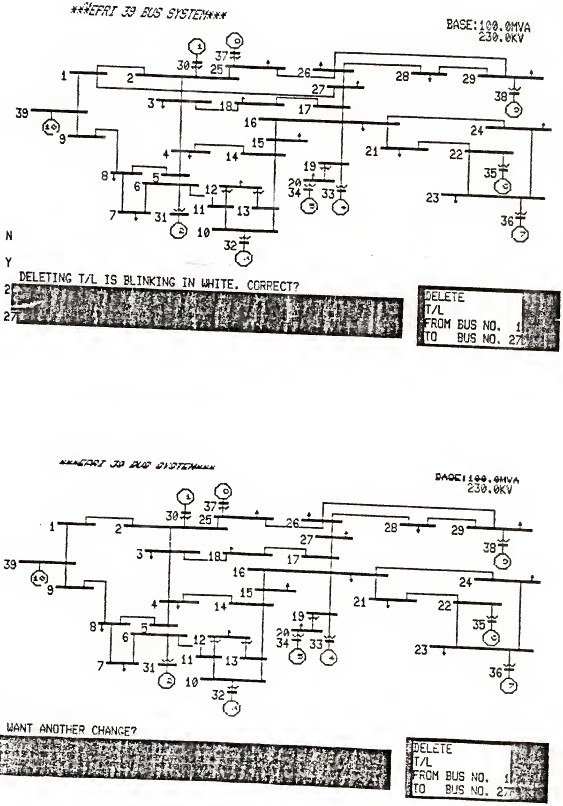
data locations are fixed, coordinates are saved for future use.

5). Transmission lines(T/L) can be added or deleted interactively. Once the deleting command is given, corresponding T/L starts blinking for confirmation before it is deleted. Refer Fig. (5.3) and Fig. (5.4).

6). As a series of interactive commands are given, command records are followed up and displayed the lower right corner of the screen for confirmation and reference. Refer to Fig. (5.3) and Fig. (5.4).

7). Any power flow or sensitivity analysis method can be selected interactively using a menu. The results are displayed either on the one line diagram or in a tabular form. They are stored in an output file for print out or future reference.

Further features can be added to the graphics system using a zooming or a panning facilities. Very large power systems with more detailed information can be displayed with paging facilities. Detailed information may include tap positions of tap changing transformers, circuit breaker status, power plant operating conditions, and metering information, etc..



DELETING T/L IS BLINKING IN WHITE. CORRECT?

2

27

DELETE
T/L
FROM BUS NO. 1
TO BUS NO. 27

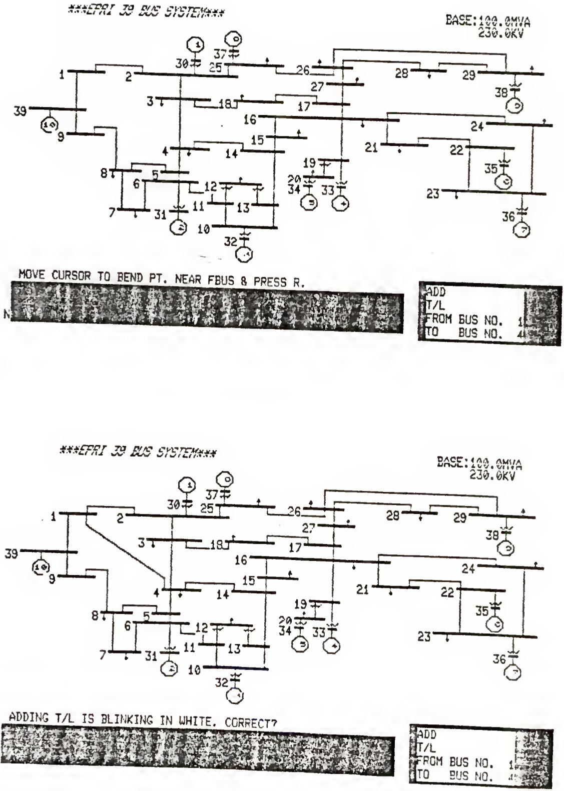
WANT ANOTHER CHANGE?

2

Y

DELETE
T/L
FROM BUS NO. 1
TO BUS NO. 27

Fig. 5.3 Interactive System Structural Change
(Deletion of T/L 1-27)



EPRI 39 BUS SYSTEM

BASE:100.0MVA
230.0KV

MOVE CURSOR TO BEND PT. NEAR FBUS & PRESS R.

ADD
T/L
FROM BUS NO. 1
TO BUS NO. 4

EPRI 39 BUS SYSTEM

BASE:100.0MVA
230.0KV

ADDING T/L IS BLINKING IN WHITE. CORRECT?

ADD
T/L
FROM BUS NO. 1
TO BUS NO. 4

Fig. 5.4 Interactive System Structural Change
(Addition of T/L 1-4)

5.2 Application of Knowledge Based System to Power System Steady State Control

The main purpose of this section is to provide some basis for applying a Knowledge Based(KB) systems methodology in solving power system steady state control problems.

The reasons for using a KB system in power system control are:

1). To produce proper, consistent and feasible control decisions which reflect a large amount of appropriate but diversified information about the power system without omitting any crucial information.

2). To facilitate changing the control decisions by simply modifying the appropriate Knowledge base, thus enabling operators to conveniently upgrade their control procedures.

3). To free operators and planners from dealing with routine problems so that they can concentrate on more innovative or creative tasks.

4). To provide training for systems operators and/or planners through an appropriate user interface.

5.2.1 KB system development steps

The necessary steps for applying a KB system to power system steady state control problems are described in this section. Related references are listed in the Reference List [46-50].

A. Knowledge conceptualization and identification step

An appropriate knowledge base can be conceptualized and specified using three basic building blocks: Unit knowledge, Relational knowledge, and Control knowledge.

1).Unit (Atomic) knowledge ; This knowledge includes the following categories of information:

a. current operating state
b. contingency test results
c. topological information
d. power plant capacity information (rated, short time, minimum, current available capacities, etc.)
e. power plant type information (hydro, nuclear, oil firing, coal firing, diesel engine, pumped-hydro; peaker, mid range unit, base load unit, etc..
f. weather information (tornado, storm, heavy snow, freezing temp., jelly fish season, etc.)
g. geographical information (seaside, river side, inland, etc.)

2). Relational Knowledge ; This knowledge includes the information which can be obtained, inferred from or affected by the unit knowledge. For example:

a. The magnitude of an available control action can be computed as the the difference between its capacity and current output.

b. The assessment of the power system state can be performed using the current operating state and/or the contingency test result,etc..

3). Control Knowledge ; This is the knowledge which controls the flow of information or the goal achieving process in the system. Thus, the knowledge can either be expressed explicitly in the rules or be embeded in the flow control of the system. The following are examples of the control knowledge:

a. Knowledge of how to apply the rules

b. Knowledge of how to process the user query

c. Knowledge of how to modify or update the knowledge base

B. Knowledge acquisition step

The explicit knowledge identified in Section A can be collected or determined from one of the following sources:

1). Analyses

a. Power flow analysis ; Power flow analyses can can be used to estimate the current operating state or to confirm the resulting state of a given control action recommended by the KB system.

b. Sensitivity analysis ; Sensitivity analyses can be used to quickly estimate the approximate system state.

c. Contingency test ; Contingency tests can be performed to assess the system security level. The results of the contingency tests can be estimated using the sensitivity methods developed in the previous chapter.

2). Expertise

Expertise may include

a. Experience

b. Heuristics

c. Assumptions

C. Knowledge representation and the KB system implementation

The knowledge formalized in the previous section should be mapped into a proper representational framework. The representation should be flexible and powerful enough to exhibit the intended level of intelligence. The trade-off between the flexibility and the efficiency should be coordinated. Any form of representation can be used, such as a property list, a sementic net, a unit frame, an associative tuple, a production rule, or other specific list format or an array.

The KB system should be implemented such that it can perform the following tasks:

1). Assess the system state; For the present operating state or the post-contingency state, the voltage and the line flow violations should be checked. If violations are detected, information related to those violations should be reflected to the appropriate knowledge representations.

2). Set the goal state region ; As a result of the state assessment, if the current operating state is unacceptable, the KB system should define a feasible goal state.

3). Determine the control action magnitudes and their application sequences; Once the goal state is set, it is necessary to choose various control actions which can transfer the system from the current operating state to the goal state. A subsequent state after taking a specific control action is approximately predictable using the system sensitivity information or from the system operational experiences, etc.. One of the basic assumptions which can be used in selecting the control actions is:

The violations can be cleared if the current state is moved in a direction opposite to the direction of the violation.

The necessary amount of move is considered to be the same as the amount of the violation.

Apparently, this assumption is valid within the range where the linearity of the state is well preserved. Otherwise, weighting factors can be used for the amount of necessary change.

Depending on the availability or preferrability, control actions can be grouped into three categories as follows:

a. Normal control actions ; These are the control actions which are normally available without any specific risk or economic losses. For example, generation change within the rated capacity of a power plant can be included in this catagory.

b. Emergency control actions ; These are the control actions which should be taken in case of emergency and which involve certain risks or substantial economic losses if they are adopted. For example, generation change of a power plant or a var control equipments within the range of their shortime ratings, or load shedding of non-critical customer loads can be included in this category.

c. Critical control actions; These are the control actions which should be taken in the face of the extremis state. For example, power plant forced shutdown, overloaded T/L trip or load shedding of critical loads may be included in this category.

4). Predict the post-control state and actual state assessment; The post-control state can be quickly approximated using the sensitivity information. Finally the expected state after applying a set of control actions can be obtained using the sensitivity methods described in the previous chapter. If the power mismatches corresponding to the approximated state computed using the sensitivity method indicate large errors , then accurate power flows can be obtained using one of the power flow methods in GPF.

5.2.2 Program development

The following is a simple example which illustrates the basic features of the proposed KB system.

A. Knowledge acquisition

All the necessary information can be collected and stored in the appropriate list formats.

1). Bus information

```
BUS( bus no. ) =
             ( bus type, total no. of connected buses,
                  ( connected bus A, B, C, ....... ) )
```

where

```
bus type :
            - swing bus  ;  S
            - voltage bus;  V
            - load bus   ;  L
```

2). Transmission line information

TL(TL no.) = (connected bus i, connected bus j, Yij, MW capacity in PU)

3). Generator information

GEN(gen no.) = (P-LIST, Q-LIST)

where P-LIST and Q-LIST are another list such as

P-LIST = (rated output, available output, short time capacity, min. output, current output)

Q-LIST = (max. Q, min. Q, current output)

where

short time capacity : the generation output capacity available only for short period of time.

min. output : possible minimum real power output which is usually decided by the boiler minimum flow or the possible stable throttling of the turbine steam control valves.

max. Q : maximum possible Q output which can be decided by the generator thermal capacity curve and the current MW output.

min. Q : minimum possible Q output within the stability limit.

4). Load information

LOAD(load no.) = (CURRENT-LOAD, CRITICAL-LOAD)

CURRENT-LOAD = (Pd, Qd)

CRITICAL-LOAD = (Pdc, Qdc)

where, CRITICAL-LOAD is a load which can be shedded only in the extremis state.

5). Capacitor information

CAP(capacitor no.) = (Cmax, Cmin , Cpresent)

6). Contingency test information

```
CONTIN( contingency no. ) =
                       ( (cause 1, component no.)
                         (cause 2, component no.) ... )
```

where, the causes can be generator drop or redispatching, load drop or management, or TL fault.

7). Sensitivity information

H(controlled bus no., control action no.) = H(i,j)

L(controlled bus no., control action no.) = L(i,j)

where, H(i,j) and L(i,j) are the ijth elements in the Jacobian submatrices respectively.

B. Knowledge representation

Based on the contingency test results, all the voltage magnitudes and real power flow violations should be examined. If violations exist, the following violation lists can be formulated.

1). Voltage violation

```
VOLT-VIO-LIST =
( (contingency no. (bus no. A, violation magnitude)
                   (bus no. B, violation magnitude) ..)
  (contingency no. ( .. , .. ) ( .. , .. ) ...........)
                 .....................               )
```

where

```
upper limit violation : + sign
lower limit violation : - sign
```

2). Line flow violation

```
FLOW-VIO-LIST =
 ( (contingency no. (line no. A, violation angle)
                    (line no. B, violation angle) ...)
   (contingency no. ( .. , .. ) ( .. , .. ) .........)
                    ...............                  )
```

where

violation angle : δij computed from $Pij \cong |Yij||Vi||Vj|\delta ij$

C. Rule execution and stopping criteria

Rules can be defined to identify a sequence of necessary control actions and their magnitudes to move the system state to an acceptable goal state. For example, the goal state can be defined as a state where all the voltage magnitudes and the real line power flows are acceptable for the tested set of contingencies.

Each rule is composed of a premise and an action part. Rule scanning can be performed according to the preset order. During the rule scanning cycles, if the premise part of a rule is satisfied, then the action part of the rule is executed. Whenever a rule is executed, the appropriate Knowledge Base is modified or sometimes the flow of the rule scanning is interrupted. Because of this KB modification, some of the rules whose premise part have not been satisfied previously become applicable in the new rule scanning cycles. The rule scanning cycle continues until one of the following conditions are satisfied.

i. Are all the violations cleared or is the goal state achieved ?
ii. Is there no more control action available ?
iii. Is there no more control action which is effective ?

If one of these conditions are satisfied, the program exits the rule scanning cycle and reports the results.

D. Specific consideration

Some of the specific points which can be considered in developing the program are:

1). Control action lists and their hierarchies

As mentioned in section C, control actions can be grouped into three categories: normal, emergency and critical control actions. When the program is initiated, normal control actions are applied first until there is no more available or effective normal control action. All the available normal control actions can be initially contained in the NORM-CONT-ACTION-LIST together with their available magnitudes. If a control action is applied, the magnitude of the appropriate control action is modified. If the remaining magnitude becomes zero, that control action is deleted from the list. Thus, the availability of control actions can be checked by determining if the NORM-CONT-ACTION-LIST is empty. If no more normal control action is available and the goal state has not been achieved, the KB system can ask the user whether it may proceed to apply the emergency control actions. Similar procedures can be implemented until either the goal state is achieved or the CRIT-CONT-ACTION-LIST becomes empty. If the violations can not be totally resolved until the critical control action list becomes empty, then the goal state cannot be achieved with the current available control actions.

2). Effectiveness of a control action

Control actions can be selected based on the sensitivity informations. More precisely, the control action which alleviates the overall violation most effectively can be selected each time. Whenever each control action is applied, the effectiveness of that control action should be checked by computing the total reductions in the magnitude of violations. This can be done by recomputing the improved system state using the sensitivity method. The accuracy of this approximate state can be checked by examining the power mismatches. If the power mismatches exceed preset criteria, iteration can be performed to increase the accuracy of the computed state.

The overall violation is the weighted sum of the violations where the large violations are weighted more heavily. If the application of a specific control action produces insignificant results, the control action can be labeled as ´not effective´ and may not be selected.

3). Cause of a contingency among control actions

A certain control action can also be the cause of a contingency at the same time. For example, a generator drop is a contingency but the output of that generator can be used to control the system state. Apparently, the output of a dropped generator can not be used to clear the violation which was caused by the same generator. This can be done by checking the CAUSE in the violation record list. If the cause of a certain violation is coincided with the selected control action, the magnitude of that violation should not be updated.

4). Restrictions in the control magnitudes and the importance of the application sequence of the control actions

One of the basic criteria in controlling the state of a power system is that the system state should always reside in an acceptable state throughout the control period. As the magnitude of a selected control action increases, all of the system states deviate from their original values. Sometimes, one of the states may reach its criteria limit even before the total available control magnitudes are exerted. In this event, increasing the control magnitudes should be discontinued and another control action that can return the state to its normal level adopted. Then the application of the original control action can be resumed.

A prototype program which shows the frame work of the proposed KB system approach is attached in Appendix 1. As an AI language, Harris LISP which is similar to Mac LISP was used.

5.3 Concluding Remarks

It is interesting to notice that the FD method, which is the most widely used power flow method among utilities, can be derived in the final simplification step of the GPF. Since all the derivations, starting from the Improved Version 1 of the EC Method, are based on the simplification of the power series expansion of the matrix $\{ I- (L^{-1}JH^{-1})K \}^{-1}$, the convergence characteristic of the FD method are naturally expected to be largely affected by the condition of this expansion. For example, matrix A can be expanded using the power series only if

spectral radius of $A < 1$

where the spectral radius of A is the maximum eigenvalue of A and

max. eigenvalue of $A < || A ||$

Here, $|| A ||$ is any induced norm of the matrix A. Therefore, as the magnitudes of the elements in the matrix $L^{-1}JH^{-1}K$ grow, or the magnitude of the maximum eigenvalue of the same matrix approaches unity, the FD method is expected to experience convergence problems. Indeed, as was shown in Chapter 3, the magnitude of the maximum eigenvalue of the matrix $L^{-1}JH^{-1}K$ is an excellent index for the convergence characteristics. It has been generally said that the FD method has a convergence problem as the significance of the off-diagonal submatrices in the Jacobian grows. But, GPF derivation provides a good theoretical basis for an interpretation such that the convergence problem may not be affected simply by the significance of the off-diagonal submatrices, but by the combination of all the submatrices like $L^{-1}JH^{-1}K$. To support this notion of new criteria of convergence, the maximum eigenvalues of $L^{-1}JH^{-1}K$ for the 11 Bus system and the 39 Bus system were examined for the different values of R/X ratios of the transmission lines. They ranged from -0.02 to -0.4 for the test systems at the power flow solution point, which validate the expansion of the matrix $\{ I- (L^{-1}JH^{-1})K \}^{-1}$ into a power series in the GPF derivation. Further detailed investigation of the characteristics of this eigenvalues may provide a interesting guide line for characterizing the overall convergence characteristics. For a system experiencing convergence problems, ordering manipulation of the rows and columns to reduce the size of the norm or the maximum eigenvalue of the matrix $L^{-1}JH^{-1}K$ can be made to improve the convergence characteristics.

The powerful convergence characteristics exhibited by both the Improved Version 1 of the EC Method and the Improved FD Method are encouraging. On accasion, the Improved FD Method is superior to the conventional FD Method even in the convergence speed. Further elaboration of the program is required to measure the CPU time more accurately, but the relative lengths in CPU time are not likely to vary significantly. Depending upon the specific system of interest, the Improved FD Method may be able to totally replace the conventional FD method. Considering the wide popularity of the FD method, this will be a significant contribution to the utility industry.

In the sensitivity analysis, the derivation of the transformation matrix T requires only an order of N, where N is the total number of buses, multiplications and divisions. Moreover, it is not necessary to compute $\hat{H}^{-1}$ from TH^{-1} explicitly since the RHS of TH^{-1} is multiplied by a mismatch vector. Thus, computing $\hat{H}^{-1}$ involves only 2N multiplications since T is identical with an identity matrix except two columns. Comparing with the N to the 3rd power order of multiplications and divisions required for inverting a matrix, the overall computational time of the proposed method is almost negligible. For multi-contingencies, it is only necessary to compute another T, say T_2, and simply multiply to the already computed vector, i.e., $T_1H^{-1}\Delta P$. Thus, using the transformation matrix T also greatly simplifies the handling of multi-contingency cases.

The accuracy of the Jacobian based sensitivity methods are limited to the accuracy of the method using the full Jacobian. The accuracy of the sensitivity results can be easily checked by examining the magnitudes of the power mismatches on each bus. In case of the several severe contingencies, even the accuracy of the sensitivity results based on the full Jacobian may not be enough. If the mismatches exceed certain preset criteria, one or two iterations can be performed to increase the accuracy.

The eventual goal of the KB Systems approach to power system control is to develop a methodology for power system operator that allows for the efficient and effective inclusion of both the quantitative and qualitative considerations. This KB systems application may can be extended to the power system planning in the future. The attempt made in this research is just a beginning and far from complete. But the overall approach and the devalopment can be served as a good frame work for the future work in this area. Implementation of the powerful deduction and inference capability is a natural next step in the future research. Collection of the more realistic qualitative information, such as heuristics and experiences, etc., by contacting with the actual operators in the utilities is necessary. User friendly interface is also indispensable in the knowledge based system development, which necessitate the development of a lexical analyzer and a language parser. Reflecting the probabilistic quantities may be a good addition for further improvement.

APPENDIX I

```
;
; This is a part of a LISP Program to apply a  Knowledge Based
; System to Power System Control.
;
;
; Followings are the functions to read in the analysis
; results from the system analysis program ouput and to
; formulate appropriate data structures.
;
;
        (DEFUN READ-IN-DATA ()
          (READ-IN-BUS-DATA)
          (READ-IN-TL-DATA)
          (READ-IN-GEN-DATA)
          (READ-IN-CAP-DATA)
          (READ-IN-LOD-DATA)
          (READ-IN-OPERAT-DATA)
          (READ-IN-SENSITIV-DATA) )
;         (READ-IN-CONTING-DATA)
;
;
;
        (DEFUN READ-IN-BUS-DATA ()
          (PROG ()
            (SETQ BUS (MAKE-ARRAY ´(50)) )
            (SETQ BUSDATA (OPEN ´BUSDATA ´R))
            (SETQ TOT-NO-BUS (READ BUSDATA))
            (SETQ I 1)
LOOP1       (SETQ BUS-NO (READ BUSDATA))
            (SETQ BUS-TYP (READ BUSDATA))
            (SETQ TOT-CONNECT-BUSES (READ BUSDATA))
            (SETQ J 1)
            (SETQ TEMPO-LST (LIST (READ BUSDATA)) )
LOOP2       (SETQ J (1+ J))
            (IF (> J TOT-CONNECT-BUSES)
                (GO NEXT-BUS))
            (SETQ TEMPO-LST (CONS (READ BUSDATA) TEMPO-LST))
            (GO LOOP2)
NEXT-BUS    (AS-1 (LIST BUS-TYP TOT-CONNECT-BUSES
                               (REVERSE TEMPO-LST))
                  BUS BUS-NO)
            (SETQ I (1+ I))
            (IF (<= I TOT-NO-BUS)
                (GO LOOP1)) ) )
;
;
;
```

```
       (DEFUN READ-IN-TL-DATA ()
          (PROG ()
            (SETQ TL (MAKE-ARRAY ´(100)) )
            (SETQ TLDATA (OPEN ´TLDATA ´R))
            (SETQ I 1)
            (SETQ TOT-NO-TL (READ TLDATA))
 LOOP       (SETQ TL-NO (READ TLDATA))
            (AS-1 (LIST (READ TLDATA) (READ TLDATA) (READ TLDATA)
                        (READ TLDATA)) TL TL-NO)
            (SETQ I (1+ I))
            (IF (<= I TOT-NO-TL)
                (GO LOOP)) ) )
;
;
; *  GEN(I)  : where I is a ´BUS´ No., not a gen No..
;
       (DEFUN READ-IN-GEN-DATA ()
          (PROG ()
            (SETQ GEN (MAKE-ARRAY ´(50)) )
            (SETQ GENDATA (OPEN ´GENDATA ´R))
            (SETQ I 1)
            (SETQ TOT-NO-GEN (READ GENDATA))
 LOOP       (SETQ BUS-NO (READ GENDATA))
;
; PG-LST ==
;  (RATED PG, SHORT TIME RATING(PG), MIN POSSIBLE PG, CURRENT PG)
;
  (SETQ PG-LST (LIST (READ GENDATA) (READ GENDATA) (READ GENDATA)
                        (READ GENDATA)) )
            (SETQ QG (READ GENDATA))
;
; QG-LST == (MAX POSSIBLE QG, MIN-POSSIBLE QG (-) , CURRENT QG)
;
; MAX POSSIBLE QG ==
;                   SQRT OF (( PG SHORT **2) - (CURRENT PG ** 2))
; MIN POSSIBLE QG ==  MAX GQ / 2.
;
            (SETQ MAX-QG (SQRT (- (EXPT (SECOND PG-LST) 2)
                                  (EXPT (FOURTH PG-LST) 2 ) ) ) )
            (SETQ MIN-QG (/ MAX-QG 2) )
            (SETQ QG-LST (LIST MAX-QGMIN-QG QG) )
            (AS-1 (APPEND PG-LST QG-LST) GEN BUS-NO)
            (SETQ I (1+ I))
            (IF (<= I TOT-NO-GEN)
                (GO LOOP)) ) )
;
;
;
```

```
       (DEFUN READ-IN-CAP-DATA ()
          (PROG ()
            (SETQ CAP (MAKE-ARRAY ´(50)) )
            (SETQ CAPDATA (OPEN ´CAPDATA ´R))
            (SETQ I 1)
            (SETQ TOT-NO-CAP (READ CAPDATA))
 LOOP       (SETQ BUS-NO (READ CAPDATA))
;
; CAP(I) == (MAX Q, MIN Q, CURRENT Q ),   where I is the BUS No.
;
       (AS-1 (LIST (READ CAPDATA) (READ CAPDATA) (READ CAPDATA))
                         CAP BUS-NO)
            (SETQ I (1+ I))
            (IF (<= I TOT-NO-CAP)
                (GO LOOP)) ) )
;
;
       (DEFUN READ-IN-LOD-DATA ()
          (PROG ()
            (SETQ LOD (MAKE-ARRAY ´(50)) )
            (SETQ LODDATA (OPEN ´LODDATA ´R))
            (SETQ I 1)
            (SETQ TOT-NO-LOD (READ LODDATA))
 LOOP       (SETQ BUS-NO (READ LODDATA))
;
; LOD(I) ==
;  (PD, QD, Critical PD, CRITICAL QD), where I is the BUS No.
;
     (AS-1 (LIST (READ LODDATA) (READ LODDATA) (READ LODDATA)
                         (READ LODDATA)) LOD BUS-NO)
            (SETQ I (1+ I))
            (IF (<= I TOT-NO-LOD)
                (GO LOOP)) ) )
;
;
; V(I) : current operating vtg or the vtg after the control
;        at BUS I.
; VU(I): upper limit    VL(I): lower limit
; A(I) : vtg angle at BUS I.
;
       (DEFUN READ-IN-OPERAT-DATA ()
          (PROG ()
            (SETQ V (MAKE-ARRAY ´(50)) )
            (SETQ VU (MAKE-ARRAY ´(50)) )
            (SETQ VL (MAKE-ARRAY ´(50)) )
            (SETQ A (MAKE-ARRAY ´(50)) )
            (SETQ OPERDATA (OPEN ´OPERDATA ´R))
            (SETQ I 1)
            (SETQ TOT-NO-BUS (READ OPERDATA))
 LOOP       (SETQ BUS-NO (READ OPERDATA))
;
```

```
              (AS-1 (READ OPERDATA) V BUS-NO)
              (AS-1 (READ OPERDATA) VU BUS-NO)
              (AS-1 (READ OPERDATA) VL BUS-NO)
              (AS-1 (READ OPERDATA) A BUS-NO)
              (SETQ I (1+ I))
              (IF (<= I TOT-NO-BUS)
                  (GO LOOP)) ) )

;
;
;
         (DEFUN READ-IN-SENSITIV-DATA ()
            (PROG ()
              (SETQ H (MAKE-ARRAY ´(50  50)) )
              (SETQ L (MAKE-ARRAY ´(50  50)) )
              (SETQ SENDATA (OPEN ´SENDATA ´R))
              (SETQ I 1)
              (SETQ J 1)
              (SETQ TOT-NO-BUS (READ SENDATA))
;
 LOOP         (ASET (READ SENDATA) H I J)
              (ASET (READ SENDATA) L I J)
              (SETQ J (1+ J))
              (IF (<= J TOT-NO-BUS)
               (SETQ I (1+ I))
              (SETQ J 1)
              (IF (<= I TOT-NO-BUS)
                  (GO LOOP)) ) )
;
; Followings are the main function to scan and apply the rules.
;
         (DEFUN APPLY-RULES ()
            (PROG ()
VTG-RULES   (SETQ (= APPLIED ´NO))
            (RULE1)
            (IF (= V-CORRECTION ´YES)
                (GO LINE-FLOW-RULES) )
            (RULE2)
            (IF (= V-CORRECTION ´NOT-POSSIB)
                (RETURN) )
            (RULE3)
            (RULE4)
            (RULE5)
            (RULE6)
            (RULE7)
            (RULE8)
```

```
          (RULE9)
          (RULE10)
          (RULE11)
          (IF (= APPLIED ´YES)
              (GO VTG-RULES)
;
          (RULE12)
          (IF (= APPLIED ´YES)
              (GO VTG-RULES) )
          (RULE13)
          (IF (= APPLIED ´YES)
              (GO VTG-RULES) )
          (RULE14)
          (IF (= APPLIED ´YES)
              (GO VTG-RULES) )
          (RULE15)
          (IF (= APPLIED ´YES)
              (GO VTG-RULES) )
          (RULE16)
          (IF (= APPLIED ´YES)
              (GO VTG-RULES) )
          (RULE17)
          (IF (= APPLIED ´YES)
              (GO VTG-RULES) )
          (RULE18)
          (IF (= APPLIED ´YES)
              (GO VTG-RULES) )
          (RULE19)
          (IF (= APPLIED ´YES)
              (GO VTG-RULES) )
          (RULE20)
          (IF (= APPLIED ´YES)
              (GO VTG-RULES) )
          (RULE21)
          (IF (= APPLIED ´YES)
              (GO VTG-RULES) )
          (RULE22)
          (IF (= APPLIED ´YES)
              (GO VTG-RULES) )
          (RULE23)
          (IF (= APPLIED ´YES)
              (GO VTG-RULES) )
;
LINE-FLOW-RULES   (SETQ (= APPLIED ´NO))
;
          (RULE 25)
          (IF (= FLOW-CORRECTION ´YES)
              (RETURN) )
```

```
           (RULE26)
           (IF (= APPLIED ´YES)
               (RETURN) )
           (RULE27)
           (RULE28)
           (RULE29)
           (RULE30) ) )
;
;
; Followings are the rules to move the system state
; to an acceptable state region.
;
;
        (DEFUN RULE1 (V-CORRECTION)
          (IF (AND (EQUAL HV-VIO-LST NIL)
                   (EQUAL LV-VIO-LST NIL) )
; Then
              (( V-CORRECTION-COMPLETE)
               (SETQ V-CORRECTION ´YES) ) ) )
;
;
        (DEFUN RULE2 (V-CORRECTION)
           (IF (AND (NOT HV-VIO-LST NIL)
                    (EQUAL V-SUPPRESS-POSSIB ´NOT-POSSIB)
               (AND (NOT LV-VIO-LST NIL)
                    (EQUAL V-RAISE-POSSIB ´NOT-POSSIB)
;
               ( (V-CORRECTION-INCOMPLETE)
                 (SETQ V-CORRECTION ´NOT-POSSIB) ) ) )
;
;
;
```

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Seung-Chul Lee was born on June 16, 1946 in Seoul, Korea. Lee was awarded the degree of Bachelor of Science in electrical engineering from the Seoul National University, Seoul, Korea, in February 1969. Since graduation, he has mostly been engaged in power system design, construction and operation. He also passed the Higher Civil Service Exam in 1972 and worked as a government officer between 1972 and 1974 in the Ministry of Treasury, government of Korea. He entered the University of Florida in January 1981 and was awarded the degree of Master of Science in electrical engineering in May 1982. After completing his master´s degree, Lee has been working towards his Ph.D. in the Electrical Engineering Department. He also has been involved in the intelligent unmanned vehicle development project supported by the US Department of Defence.

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I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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